KESSLER

Spring Final Review

ASEN 4028 Spring 2018

Abdiel Agramonte-Moreno, Glenda Alvarenga, Thanh Cong Bui,
Christopher Choate, Lauren Darling, Sergey Derevyanko, Cassidy Hawthorne,
Abigail Johnson, Nick Thurmes, Jannine Vela, Taylor Way

Agenda

Kinesthetic
Engineered
Solution to
Space
Litter &
Exhausted
Resources

- Project Overview
- Design Description
- Test Overview
- Test Results
- Systems Engineering
- Project Management

Project Overview

Project Overview | Design Description | Test Overview | Test Results | Systems Engineering | Project Management

Project Purpose

Project Motivation

Amount of orbital debris is set to triple by 2030 (More than 500,000 in orbit today). Consists of:

- Pieces of satellite components
- Satellites at EOL
- Malfunctioning satellites

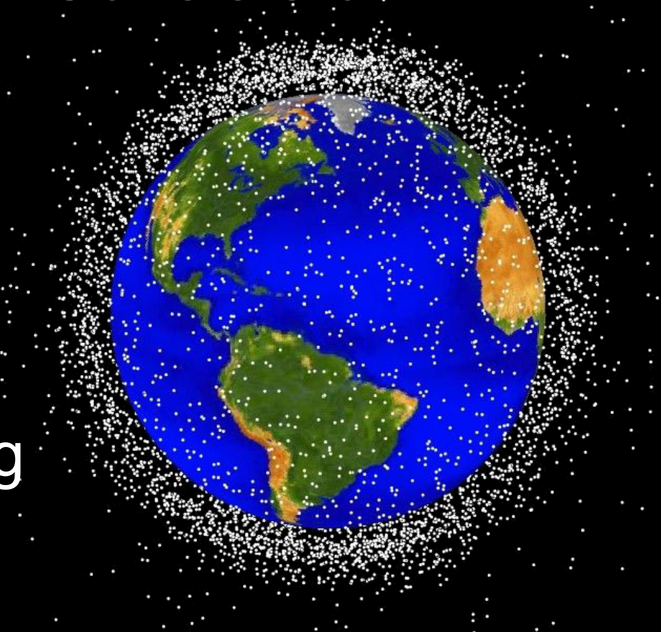


Fig. 1 Space Debris 2013 Model [1]

Sierra Nevada Corporation:

- Satellite feature recognition with an RGB sensor
- Autonomously capture feature with robotic manipulator arm

Fig. 2 SNC Developed OrbComm G2 Assets [2]

Project Purpose

Project Statement

The KESSLER project will design a system that utilizes visual processing and a robotic arm to autonomously capture space debris.

Level	Shortened Description
1	Identify Satellite, articulate arm to closest point on satellite
2	Identify features on satellite, capture feature via robotic arm
3	Identify keep out zone, articulate arm on collision avoidance path and capture feature.

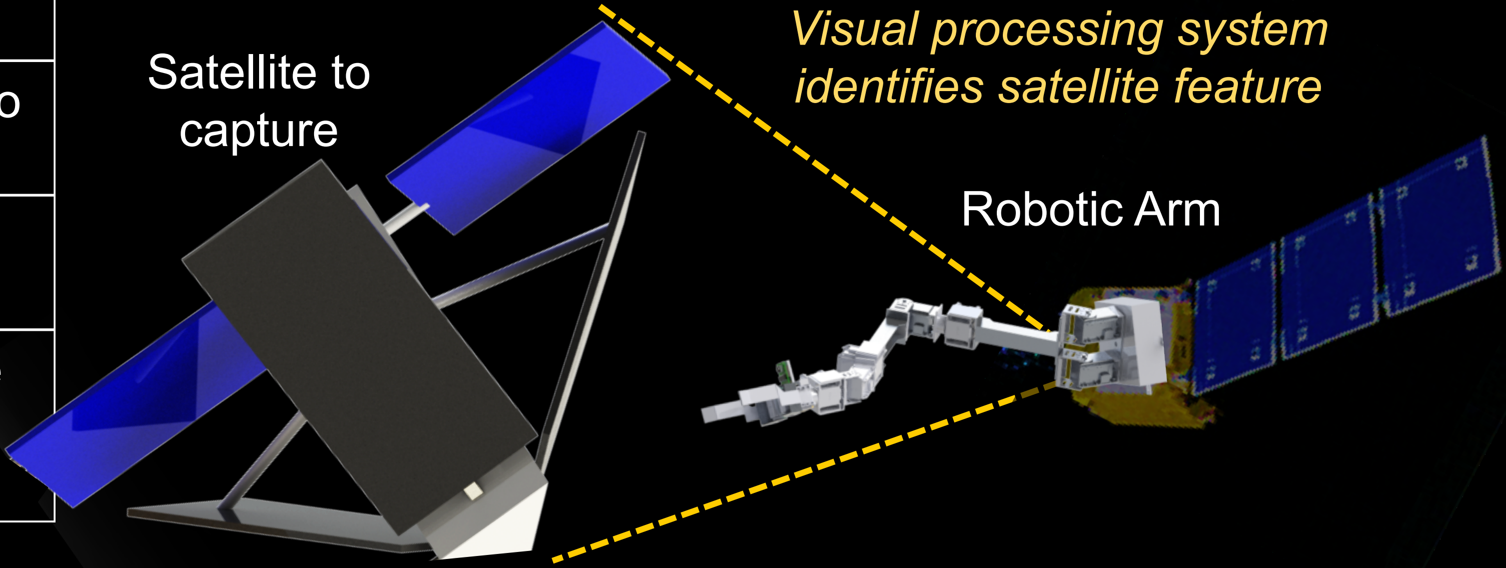


Fig. 3 KESSLER Robotic arm and vision system in process of capturing satellite in LEO

Concept of Operations

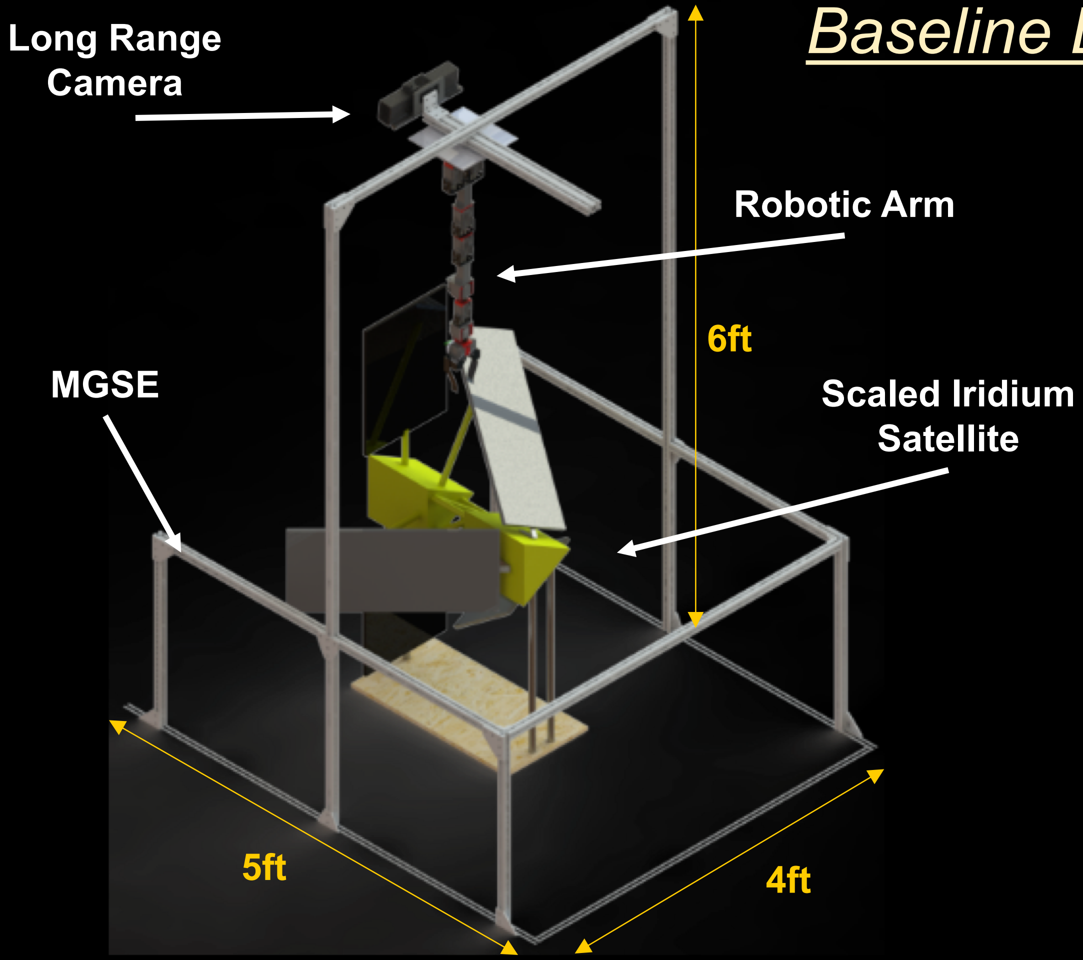


Fig. 4 KESSLER Design: Robotic Arm, Camera, Iridium Satellite, GSE

Baseline Design

0. System Initialization

Robotic arm positioned in a neutral (suspended) position and subject to uniform lighting conditions.

Long & Short Range Cameras, and Robotic Arm feature COTS components. All other are fabricated by KESSLER.

Concept of Operations

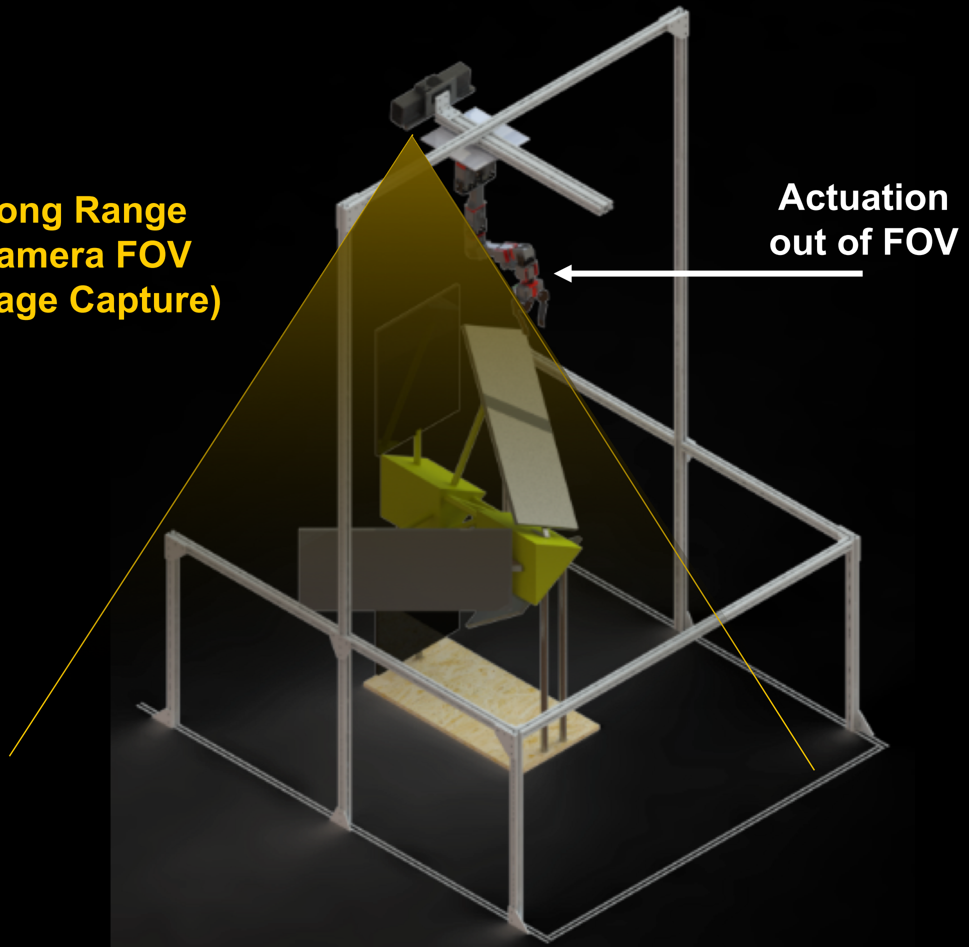


Fig. 5 KESSLER Design: Long Range Camera 2D and 3D image capture.

1. Identification of Feature

Arm actuates out of FOV of Kinect. Kinect takes long range image and identifies a feature in Field of View (FOV).

Microsoft Kinect V2: 2D (RGB), 3D (IR) image capture

Concept of Operations

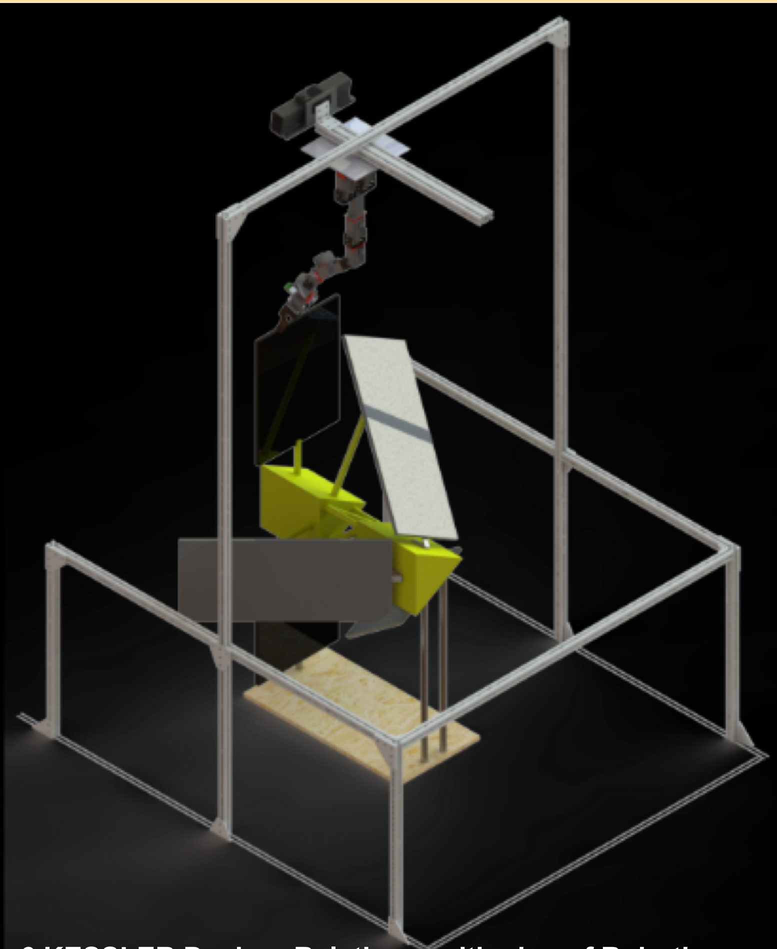
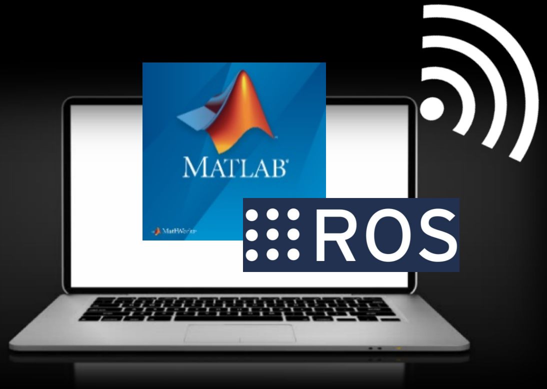


Fig. 6 KESSLER Design: Relative positioning of Robotic arm near capture location.

2. Primary Positioning

Robotic arm actuates to the relative position and orientation of the pre-defined satellite feature.



Concept of Operations

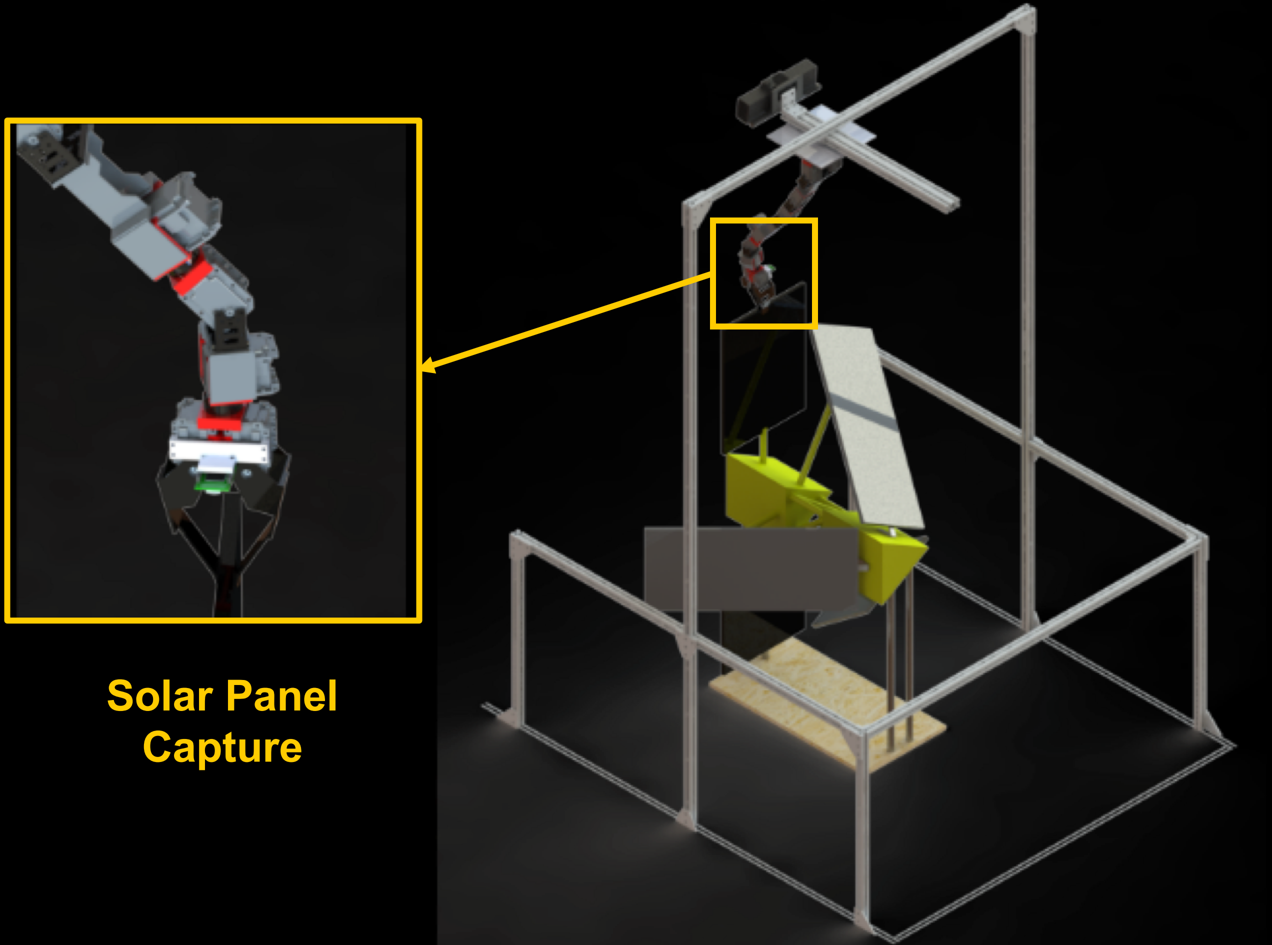
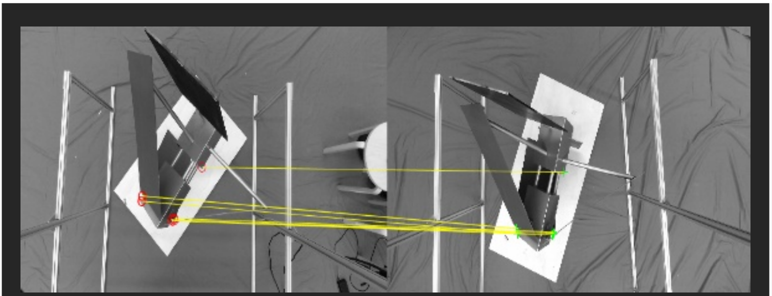
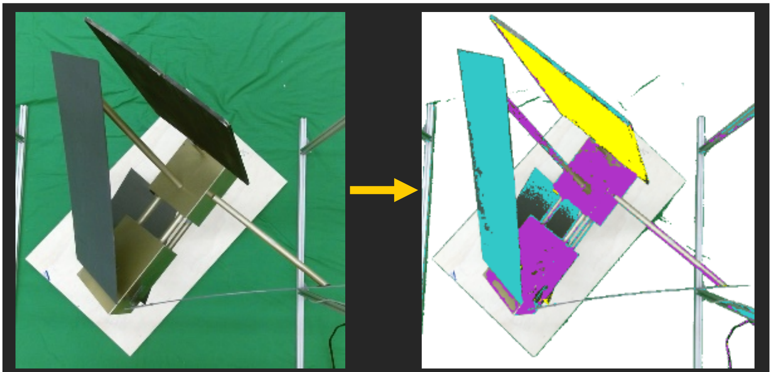
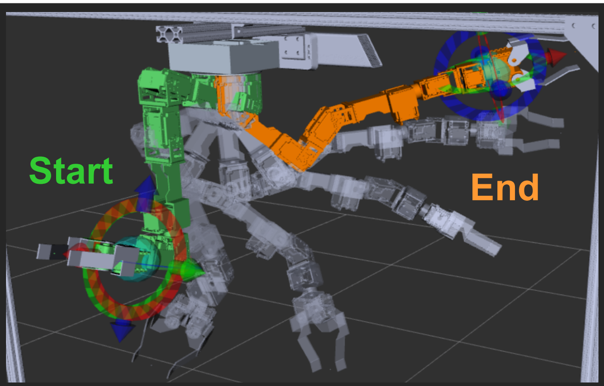
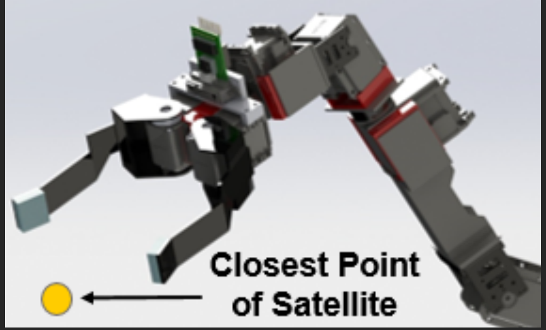
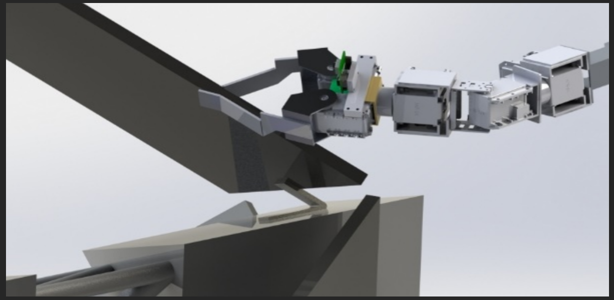
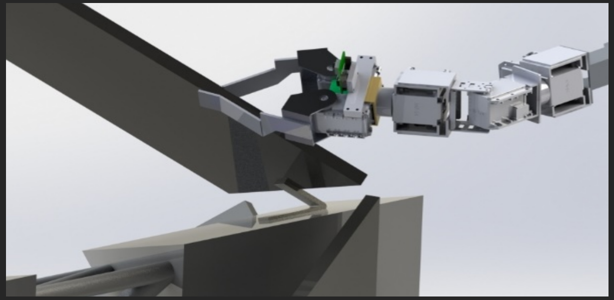

Solar Panel Capture

Fig. 7 KESSLER Design: Robot arm end-effector capturing antenna panel on Iridium Satellite.

3. Capture

Control software commands robotic claw to close on and capture the feature.

Levels of Success

Level 1	Level 2	Level 3
 Database Feature Matching	 Feature Isolation	 Path Planning
 Robotic Arm Articulation	 Solar Panel Capture	 Solar Panel Capture
Identify satellite, articulate arm to closest location on satellite.	**Identify feature on satellite, capture via robotic arm.**	**Articulate arm on collision-free path and capture feature.**

System Tolerance Stack-Up

Subsystem	Linear Error	Angular Error	Mapping
Controls	1 inch	1.4 degrees	Droop, Drift
Mechanical	0.2000 inches	1.2 degrees	Manufacturing & Encoder Error
Visual Processing	0.1575 inches (4mm)	5 degrees	Pixel Resolution
System	**2 inches**	**10 degrees**	Cumulative Error

Design Description

System Design

- Hardware supporting software is comprised of:
  - **R**obotic **O**peration **S**ystem – robotic control and software integration with visual
  - MATLAB – visual processing image analysis

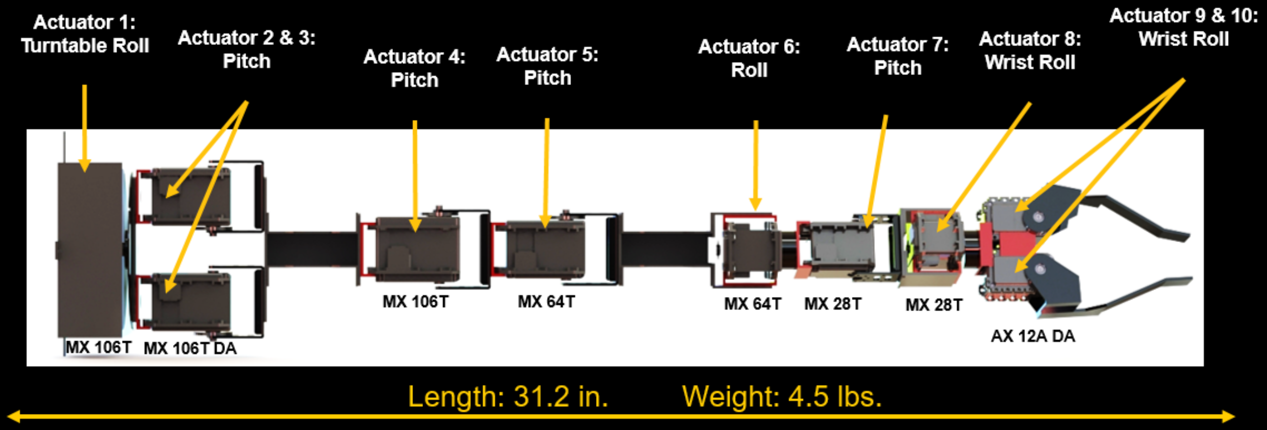


Fig. 8 KESSLER 7DOF Robotic Arm

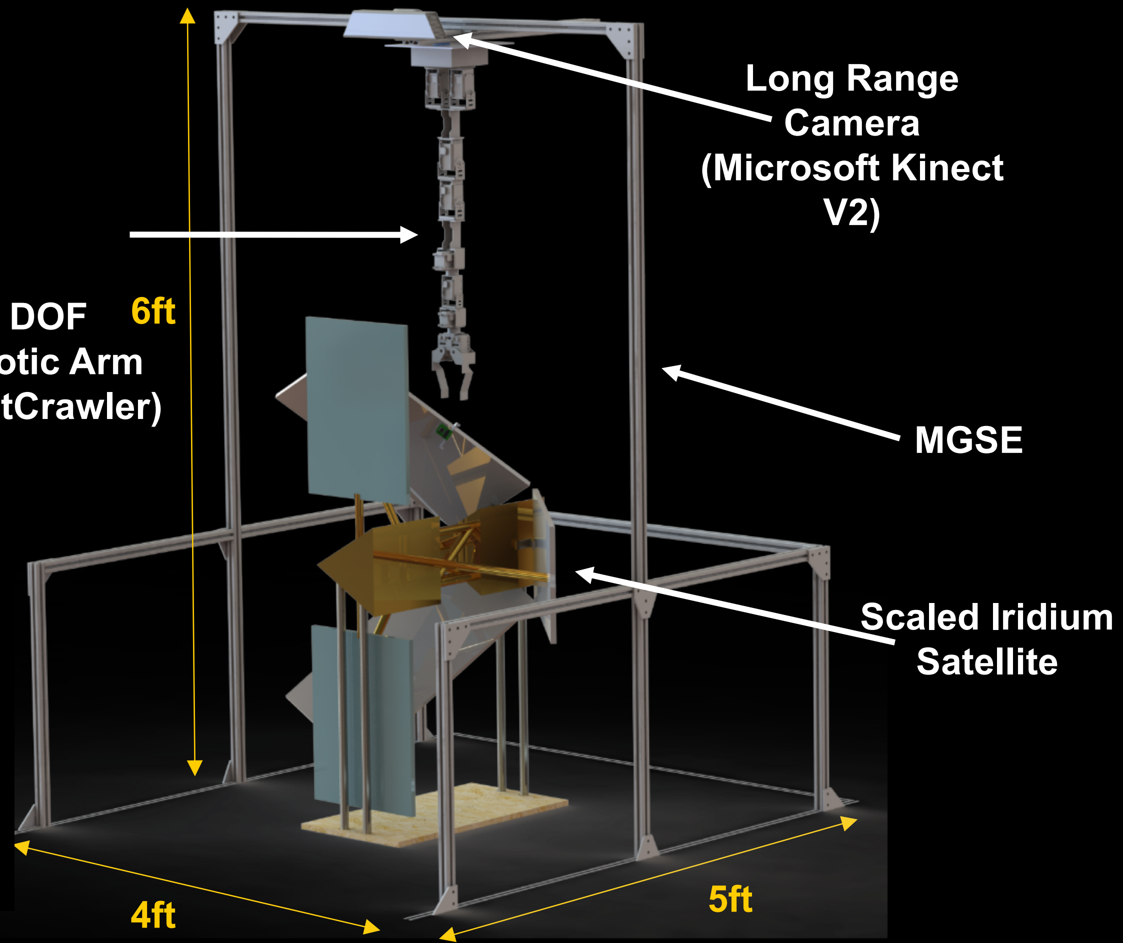
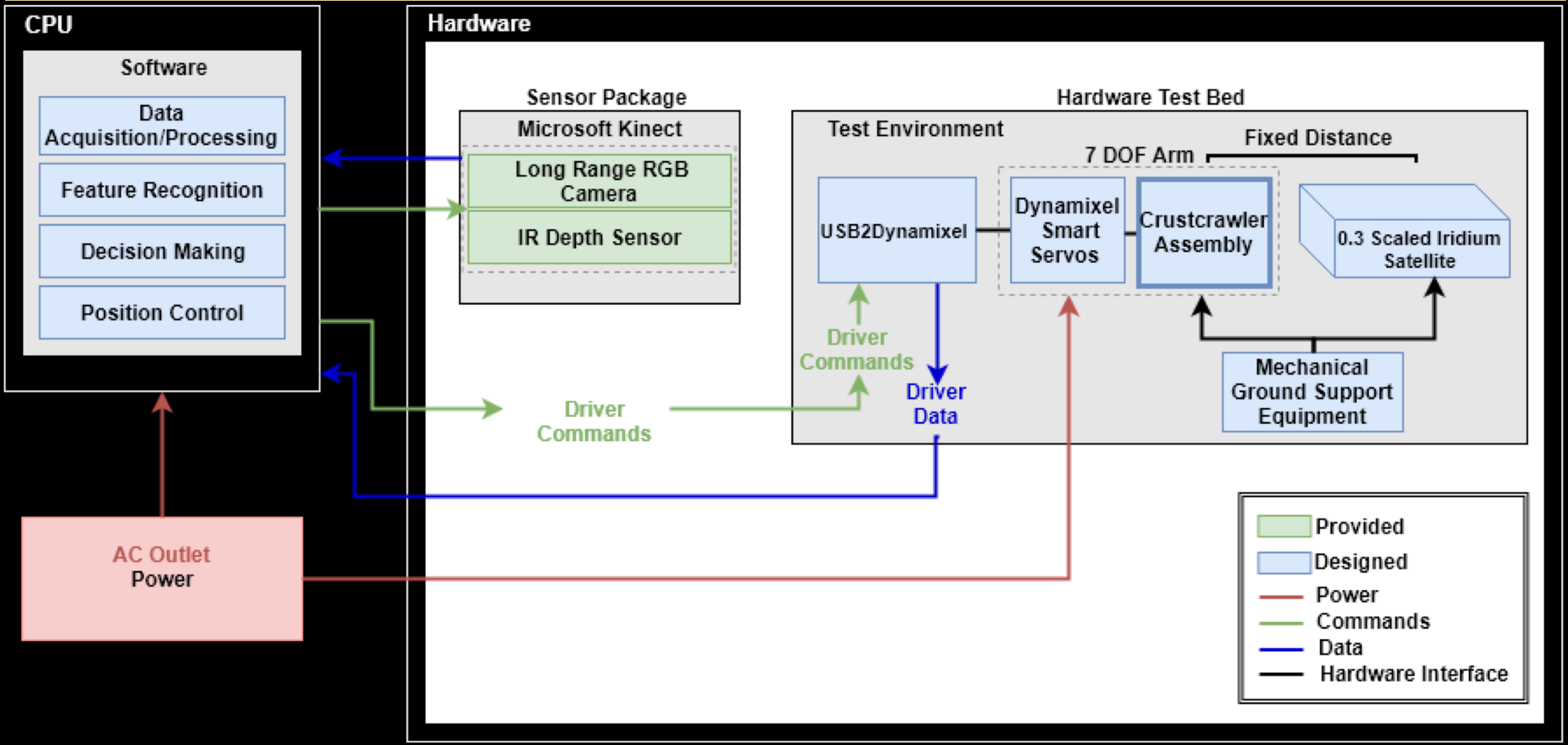


Fig. 9 KESSLER Design: Robotic Arm, Camera, Iridium Satellite, GSE

Functional Block Diagram



CPU

Software

- Data Acquisition/Processing
- Feature Recognition
- Decision Making
- Position Control

AC Outlet Power

Hardware

Sensor Package

Microsoft Kinect

- Long Range RGB Camera
- IR Depth Sensor

Hardware Test Bed

Test Environment

- USB2Dynamixel
- 7 DOF Arm
  - Dynamixel Smart Servos
  - Crustcrawler Assembly
- Fixed Distance
- 0.3 Scaled Iridium Satellite
- Mechanical Ground Support Equipment

Driver Commands

Driver Commands

Driver Data

🟩 Provided

🟦 Designed

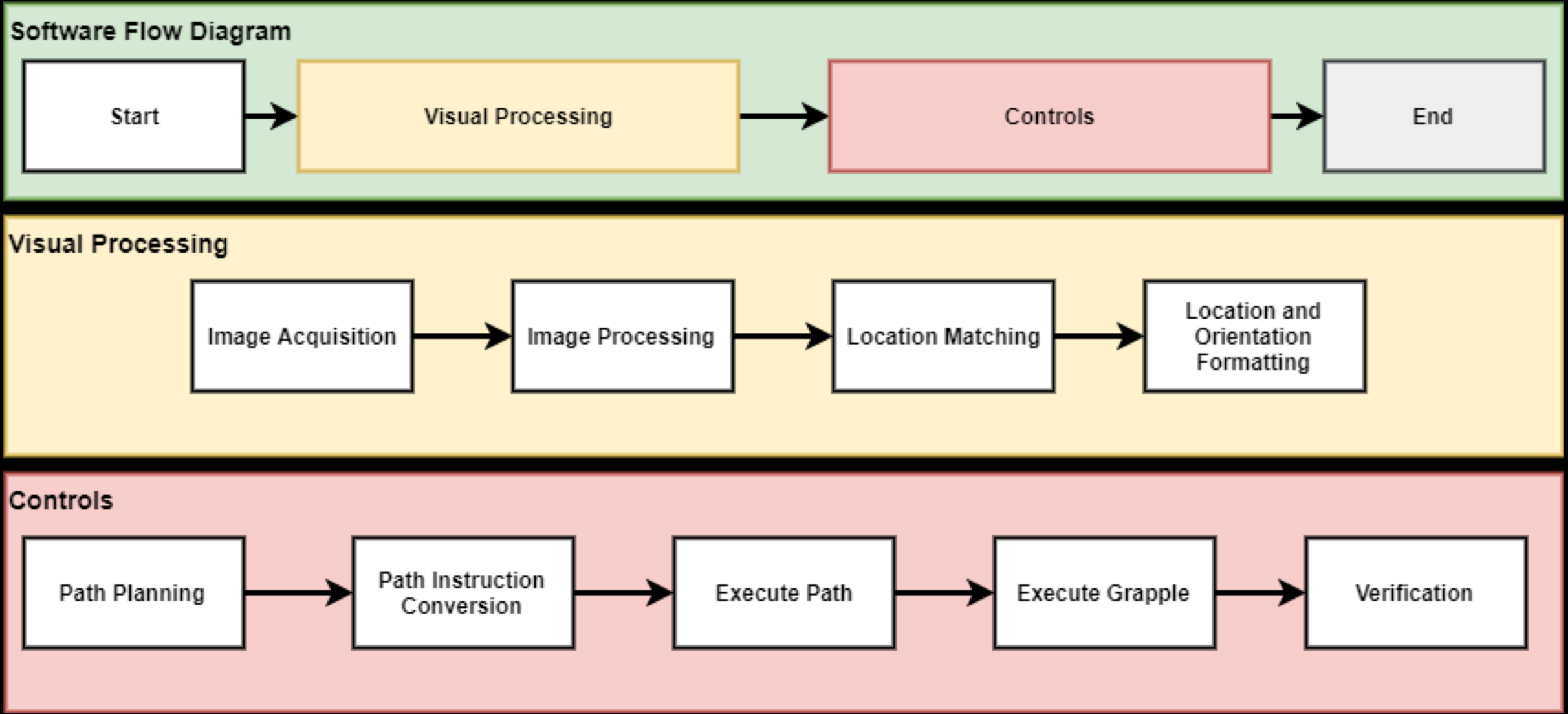
— Power

— Commands

— Data

— Hardware Interface

Software Flow



Software Flow Diagram

Start → Visual Processing → Controls → End

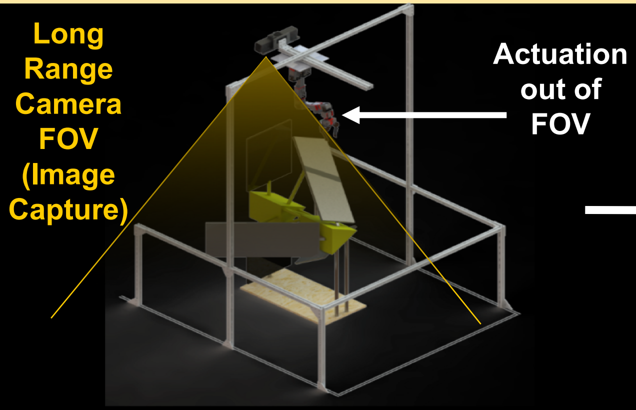
Visual Processing

Image Acquisition → Image Processing → Location Matching → Location and Orientation Formatting

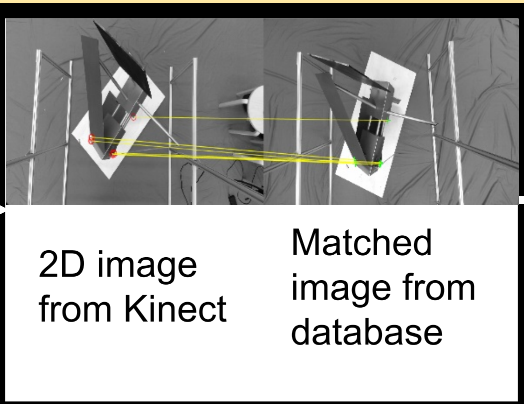
Controls

Path Planning → Path Instruction Conversion → Execute Path → Execute Grapple → Verification

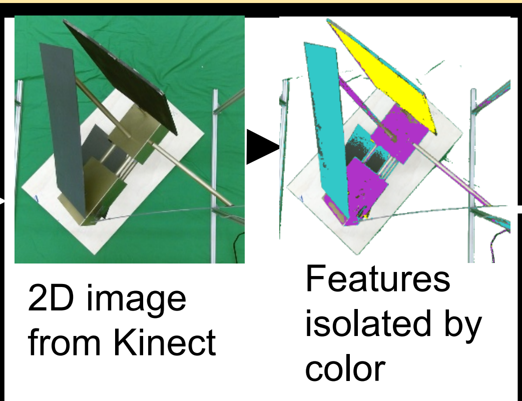
Software: Visual Processing ConOps



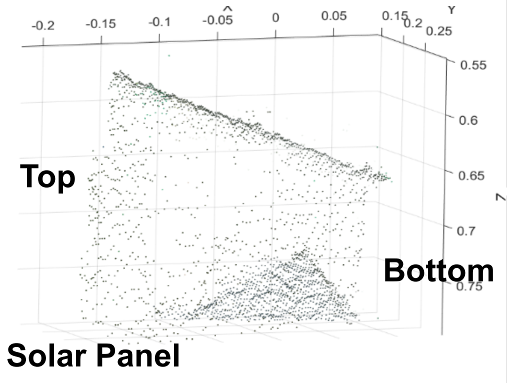
1. Take 2D and 3D image of satellite model with Kinect



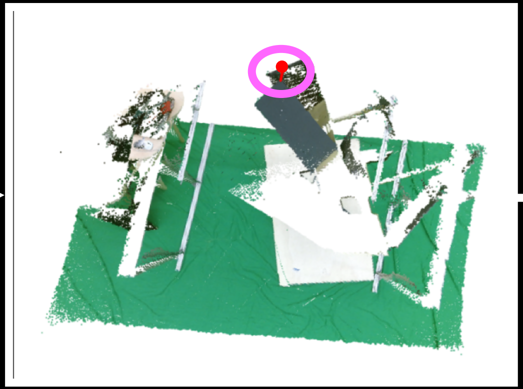
2. Identify the satellite is in the FOV



3. Identify features by color



4. Identify planes of the satellite (solar panel and antenna)

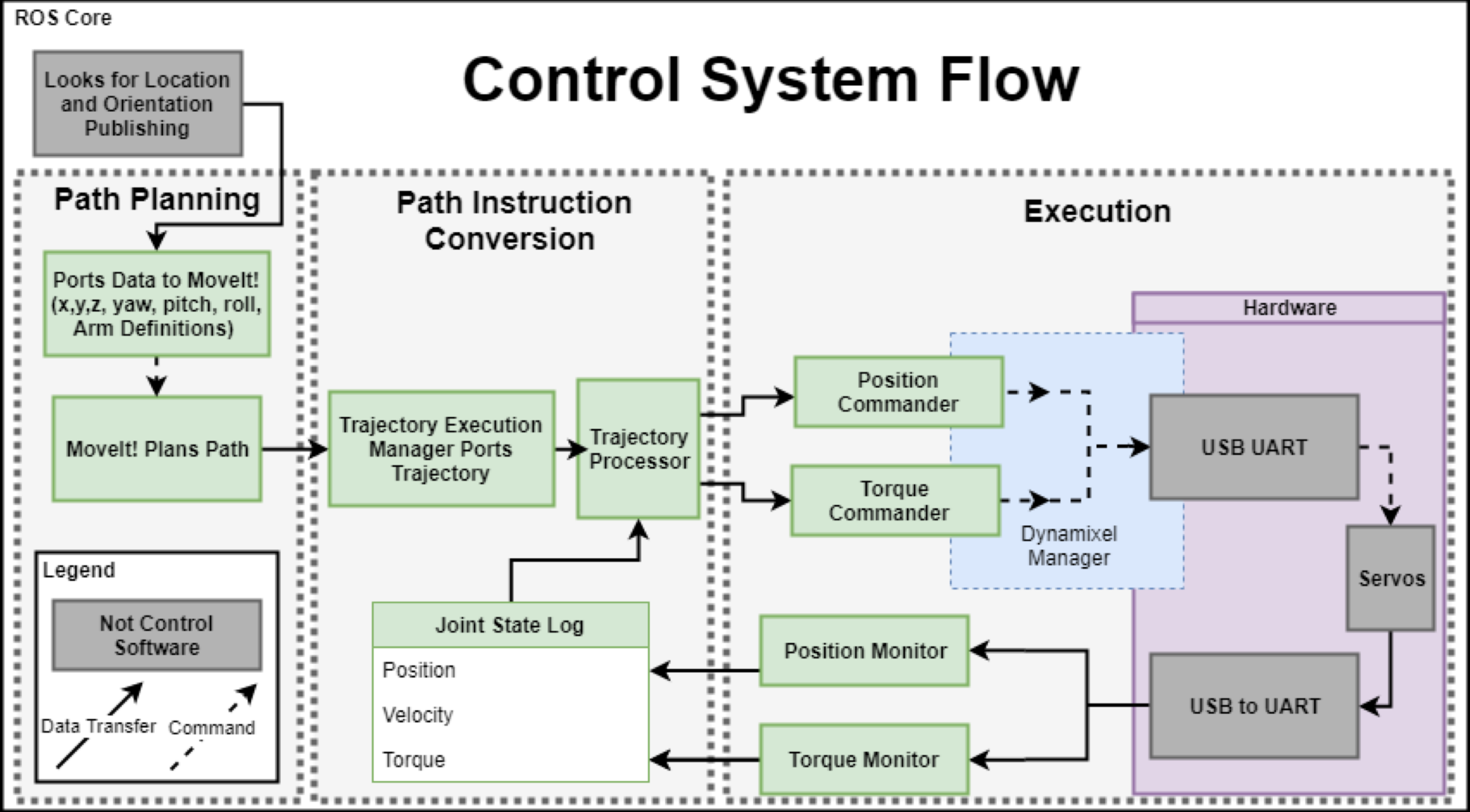


5. Find the closest point of the closest plane

Level 1: location
Level 2: location, orientation
Level 3: location, orientation, point cloud

6. Package data for controls system

Software: Controls

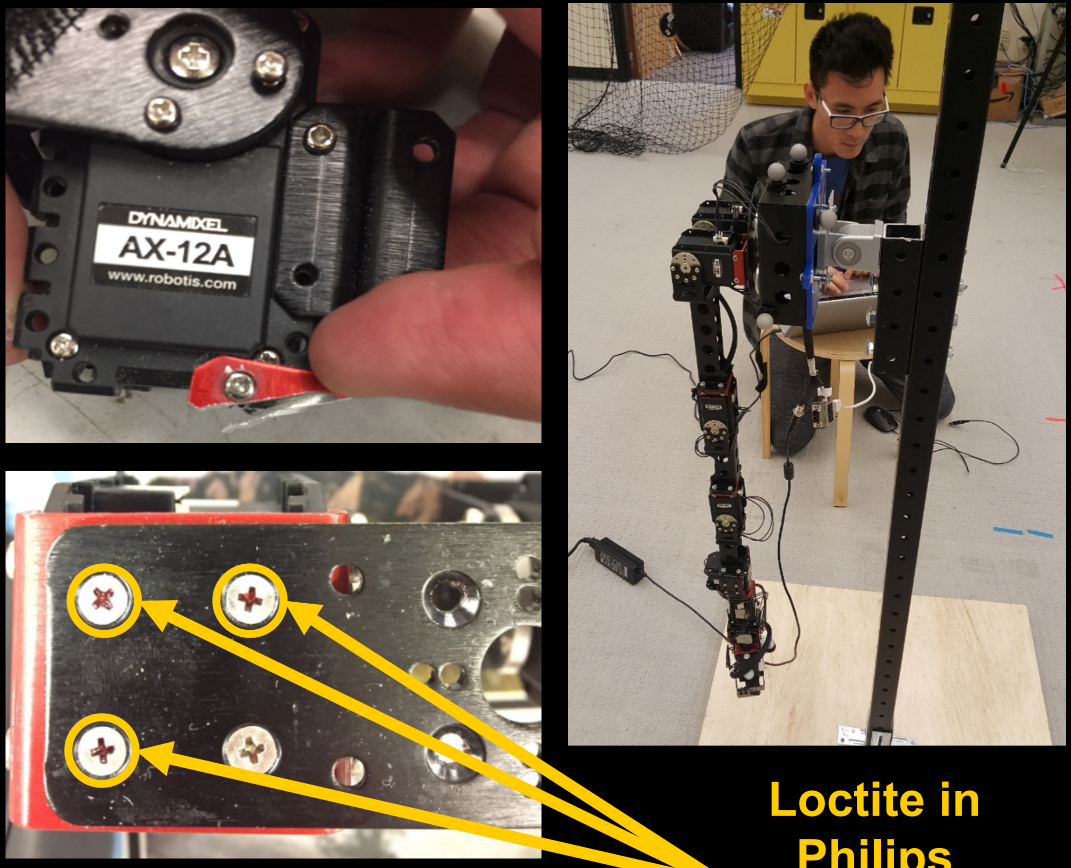


Changes since TRR

Significant Change: Robotic Arm Redesign

- Recap at TRR
  - Heritage hardware had Red Loctite on critical arm components
  - Planned test for 'low loading' configuration
  - First final integrated arm test on March 23rd

Logistical Impact:
1.5 Weeks Delay in Critical Path (Robotic Arm Checkout Test)



Loctite in Philips Screw Head

Fig. 10 Hardware Issues Encountered

Changes since TRR

Significant Change: Robotic Arm Redesign

- Post TRR
  - 'Low loading' test failed
  - Turn table and first joint (total 3 actuators) failed
  - Motors in first joint were replaced with high torque capacity motors
  - Arm was shortened by 5 inches
  - System configuration changed to remove gravitational load on turntable.
  - Short range camera (redundant) was no longer required

Minor design adjustment for visual processing. The team worked over 200 hours over Spring Break

Fig. 11 & 12: Initial suspended configuration (left), final suspended design (right)

Critical Project Elements Overview

Three Critical Project Elements

- CPE 1: Feature Recognition
  - Addresses Objectives 1 and 2
- CPE 2: Control Systems
  - Addresses Objective 3 and 4
- CPE 3: Robotic Arm
  - Addresses Objectives 4

KESSLER Project Objectives

1. Take visual data confirming the target object is within FOV.

2. Identify pre-defined satellite feature.

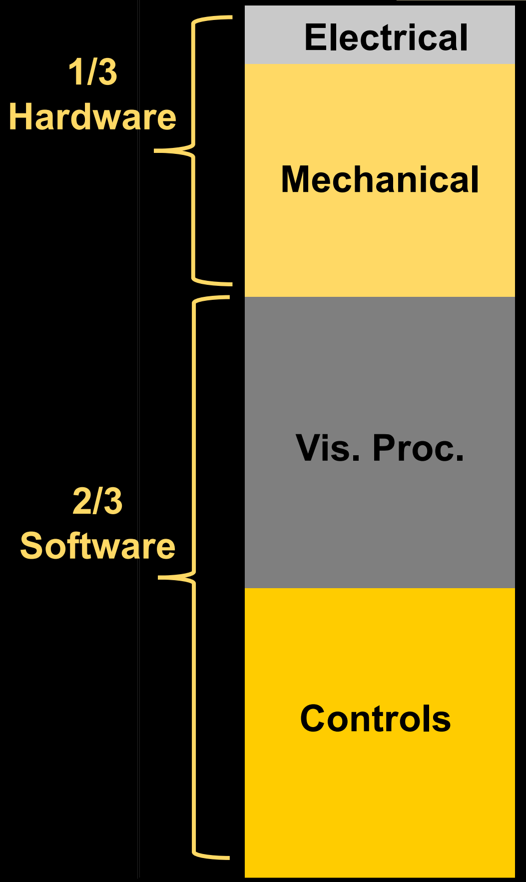
3. Determine prediction path to feature location.

4. Autonomously capture the feature via robotic arm

Test Overview

System Level of Effort

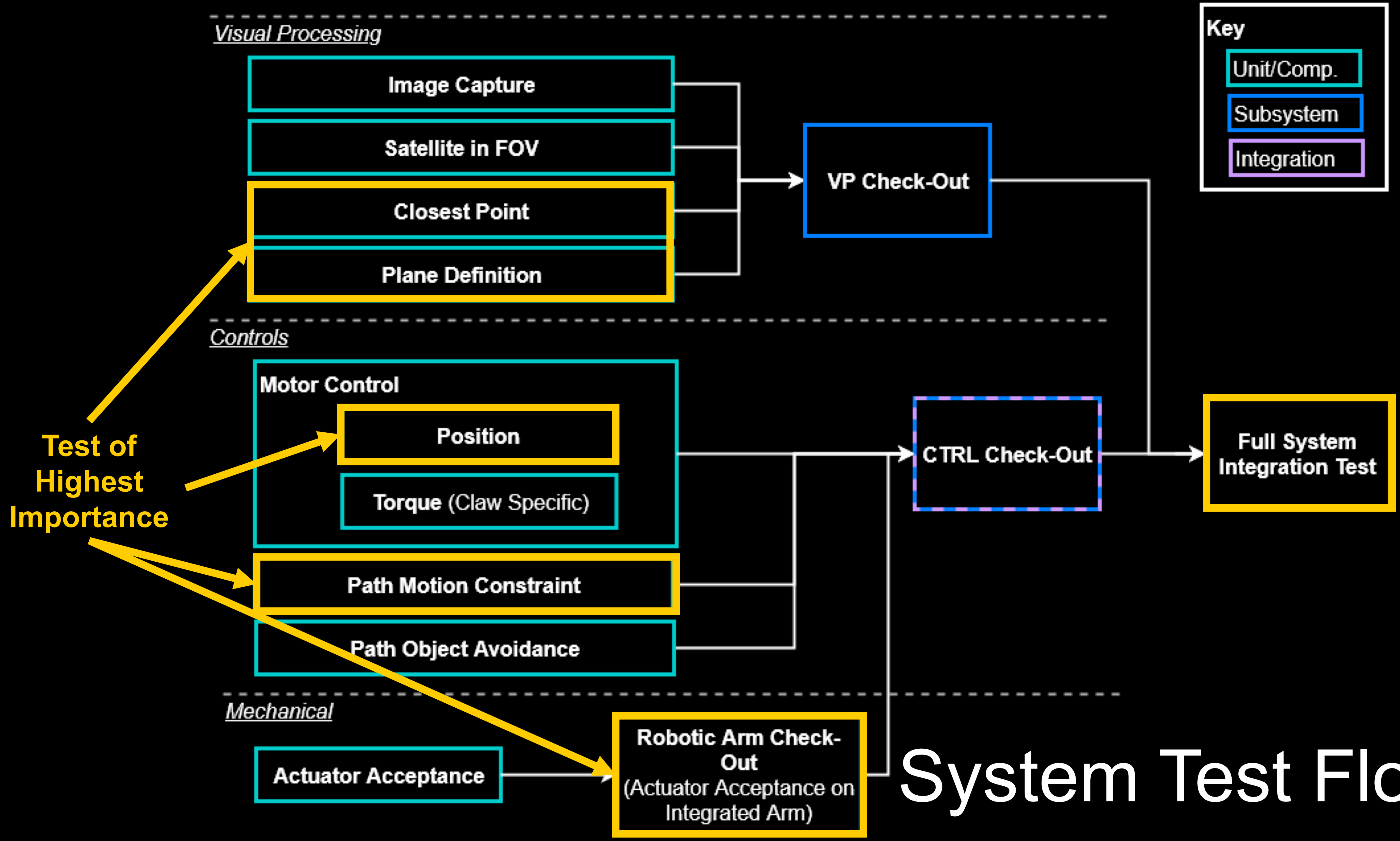
KESSLER efforts are split between Hardware & Software



Subsystem Level of Effort

- **Electrical**: Robotic arm actuators, visual processing sensor interface, electrical ground support equipment.
- **Mechanical**: Robotic arm, mechanical ground support equipment, and simulated satellite.
- **Visual Processing**: Identification of satellite and associated feature. Sends position, orientation, and satellite 3D point cloud.
- **Controls**: Path planning and executing robotic arm control.

System Test Flow



Visual Processing

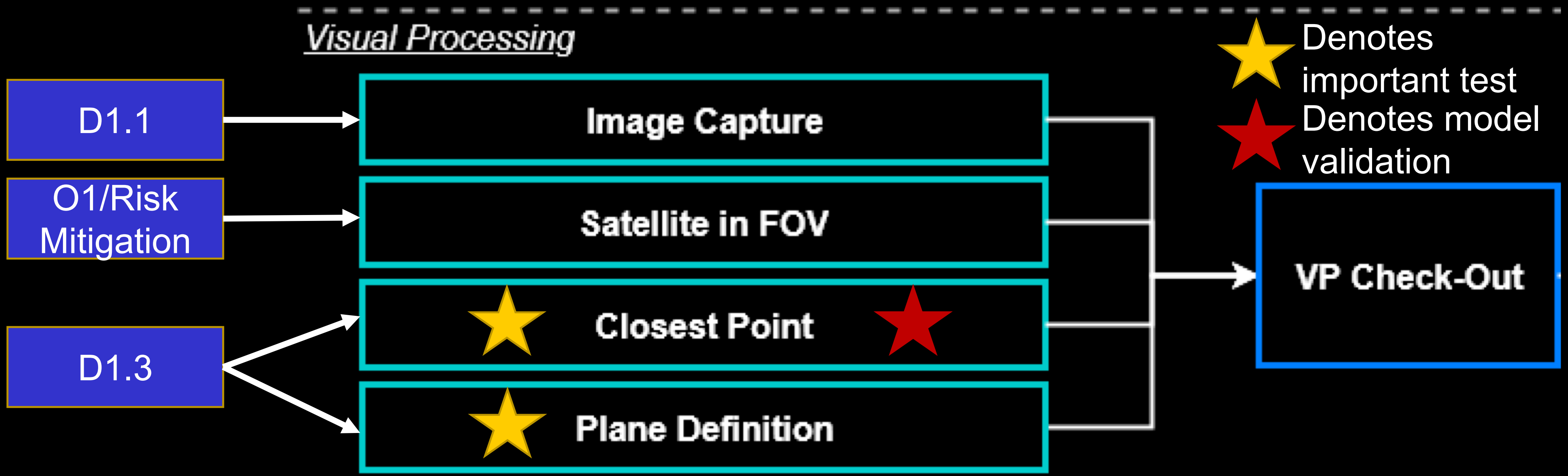
Test Overview

Project Overview
Design Description
Test Overview
Test Results
Systems Engineering
Project Management

Visual Processing Model

Input	3D point cloud from Kinect with max error 0.1 mm
VP Analysis	Identify solar panels and antenna by finding a plane in 3D point cloud and locate the closest point to the camera on the plane
Output	(x, y, z) location of closest point and quaternion for orientation to within 4 mm and 5 degrees

Visual Processing Subsystem Tests



Visual Processing

D1.1

O1/Risk Mitigation

D1.3

Image Capture

Satellite in FOV

★ Closest Point ★

★ Plane Definition

VP Check-Out

★ Denotes important test

★ Denotes model validation

D1.1 – The visual processing algorithm shall be capable of detecting a feature at a minimum distance of 20 inches

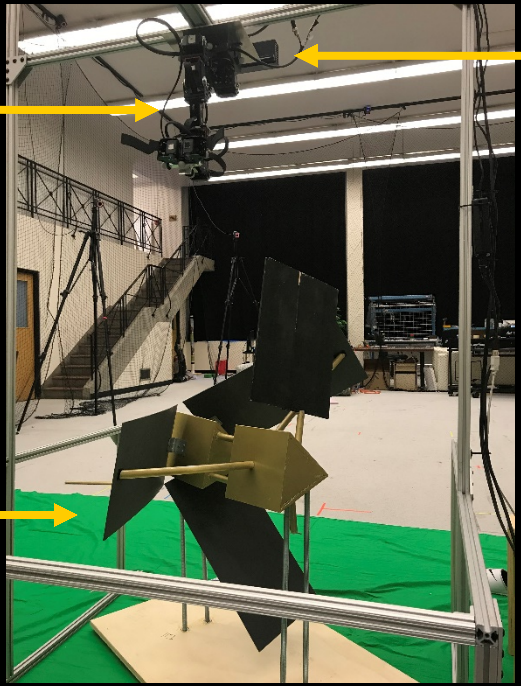
D1.3 – The visual processing algorithm shall identify the position and orientation of an object in 3D space to within 4mm and +/- 5 degrees

Define Closest Point on Planes Test Overview

Objective: Identify planes on the satellite model and identify closest point on plane

Requirements/Models: D1.3 The visual processing algorithm shall identify the position (x,y,z) and orientation (Euler angles) of an object in 3D space to within +/-4mm and +/-5 degrees.

Equipment/Facilities: 3D point cloud generated from Kinect


Robotic arm

Kinect V2

Iridium satellite model

Fig. 13 Closest Point Test Setup

Procedure:

1. Give MATLAB script 3D point cloud of satellite
2. Run MATLAB script to find and define plane(s)
3. Visually confirm plane(s) have been properly isolated and defined

Output Data:

- Closest point on plane
- Isolated plane(s)
- Orientation vector

Closest Point on Plane Model Validation

- MATLAB has camera calibration
- Took images of checkerboard of known size every 50 mm to determine error in Kinect
- MATLAB outputs maximum pixel error

Fig 14: Example of calibration testing setup

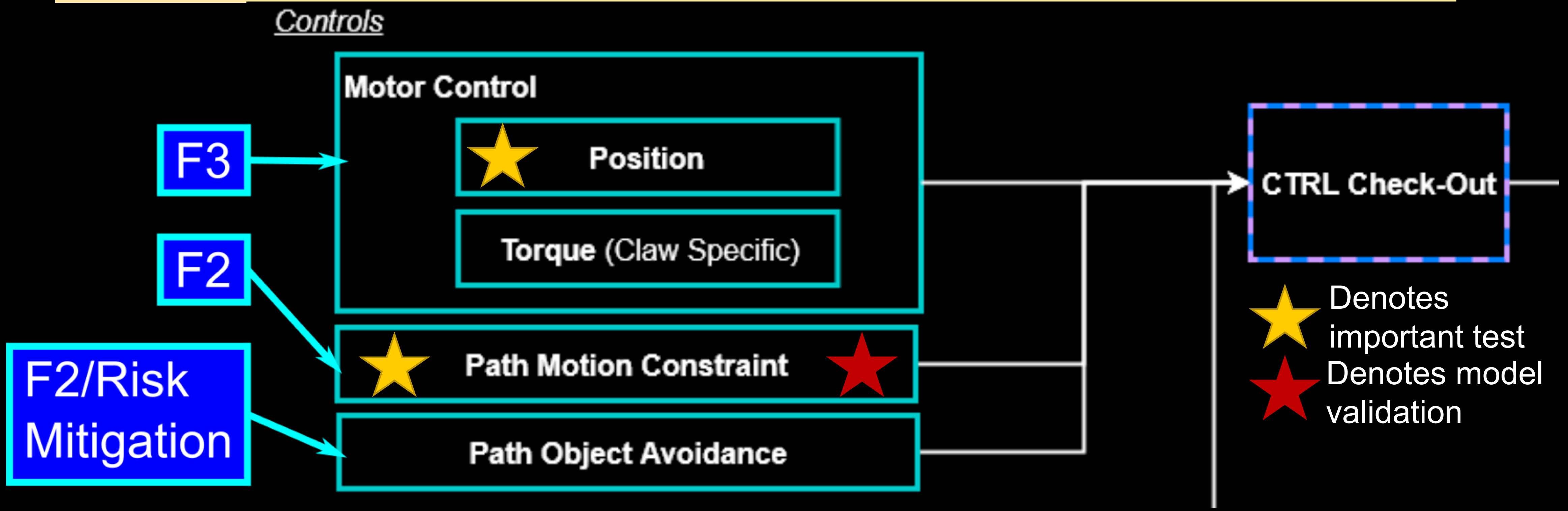
Controls

Test Overview

Controls Model

Input	Target location from visual subsystem with max error 4 mm
Path creation	Create path from initial location to target with max error 15 mm
Actuate	Send commands to motors and wait to reach desired state with max error 13 mm
Result	Reach target location with max total error 50 mm

Controls Subsystem Tests



Controls

F3

F2

F2/Risk Mitigation

Motor Control

★ Position

Torque (Claw Specific)

★ Path Motion Constraint ★

Path Object Avoidance

CTRL Check-Out

★ Denotes important test

★ Denotes model validation

F3: Robotic arm shall autonomously navigate to and secure one preselected satellite feature
F2: The control algorithm shall define a path from the initial to the final end-effector location

Motion Constraints Test Overview

Objective: Verify the motions required are achievable by the actuators

Requirements/Models: D2.2 The robotic arm path shall be constrained by the arm's joint limitations

Equipment/Facilities: Path planning algorithm

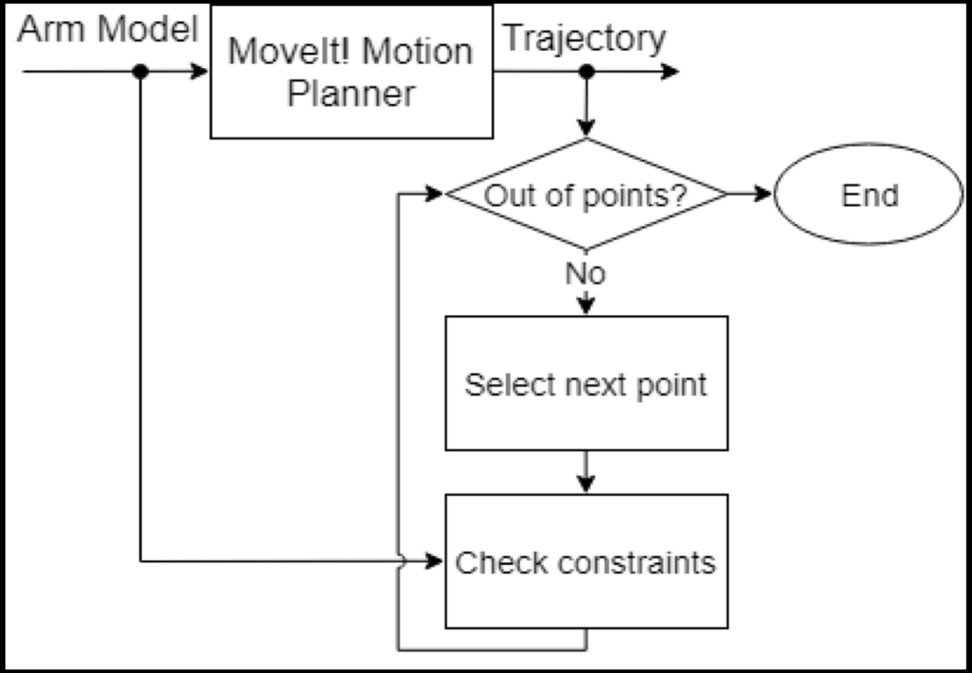


Fig. 15 Motion Constraints Configuration Setup

Procedure:

1. Create path to target location
2. Compare path to known joint limits

Measured Data:

- Joint angle
- Joint angular velocity

Arm Joint Test Overview

Objective: Move the robotic arm along a path

Requirements/Models: F3 Robotic arm will navigate to at least one preselected satellite feature

Equipment/Facilities: All arm actuators, PC, ROS MoveIt! Software

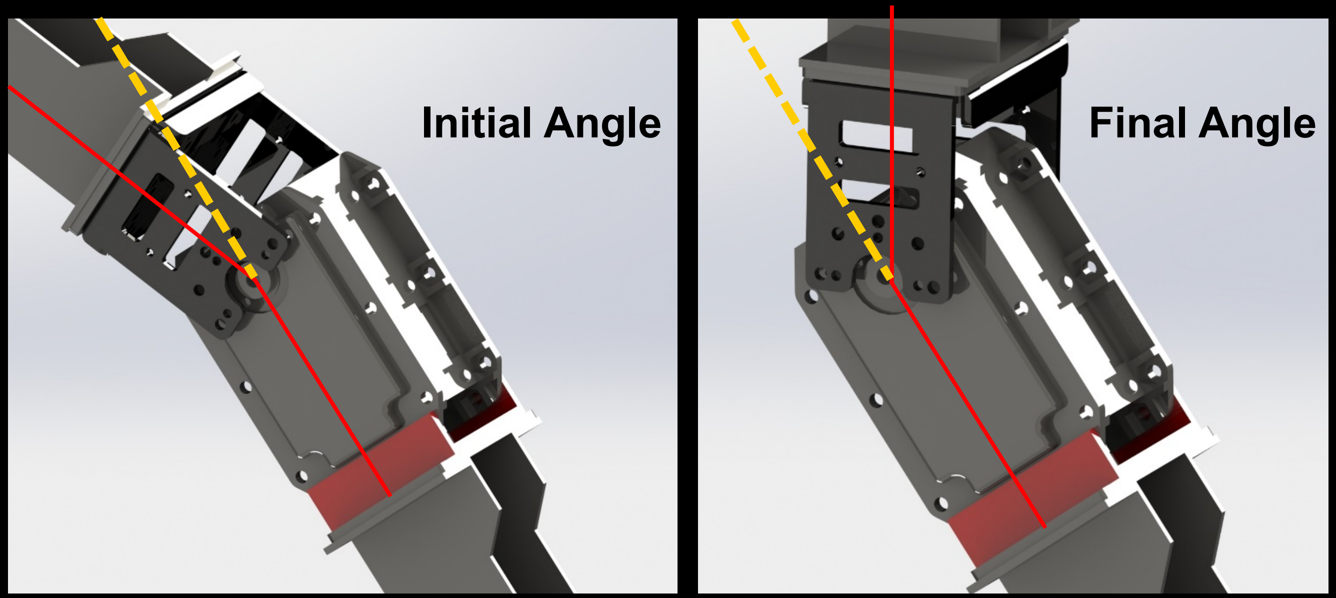


Fig. 16 Arm Joint Test Setup and measurement methodology.

Procedure:

1. Connect actuators to computer
2. Send objectives (commanded angle) to actuators
3. Monitor actuation state

Output Data:

- Position of actuator over time

Controls Checkout Test Overview

Objective: Verify location of robotic arm after actuation

Requirements/Models: F3 Robotic arm shall autonomously navigate to at least one preselected satellite feature on the satellite.

Equipment/Facilities: Path planning algorithm, point cloud as from visual, integrated robotic arm

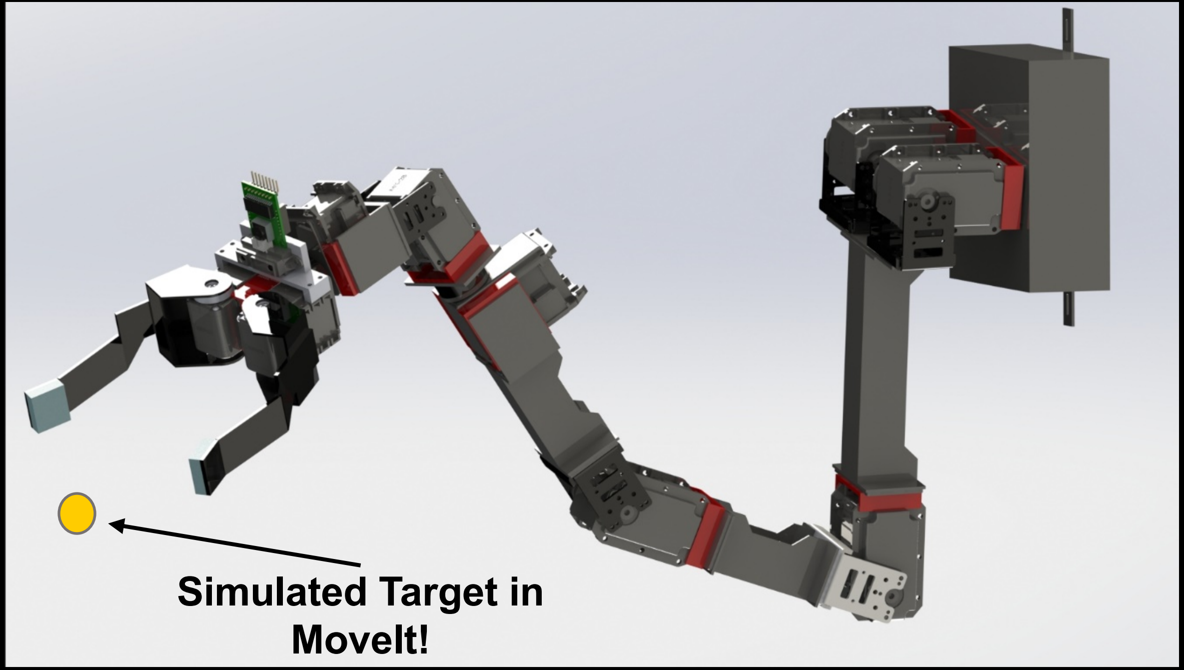


Fig. 17 Controls checkout hardware test setup.

Procedure:

1. Pass simulated target to MoveIt!
2. Follow generated path
3. Compare true final location to target

Measured Data:

- Calculated arm location
- Target arm location
- True arm location

Robotic Arm

Test Overview

Robotic Arm Checkout Test Overview

Objective: Verify that the robotic arm can withstand system loads in integrated configuration and interface with controls.

Requirements/Models: D3.1 The robotic arm shall execute commands given by the control subsystem

Equipment/Facilities: Integrated Robotic Arm, MGSE, ROS enabled CPU, Hardware I&T Lead.

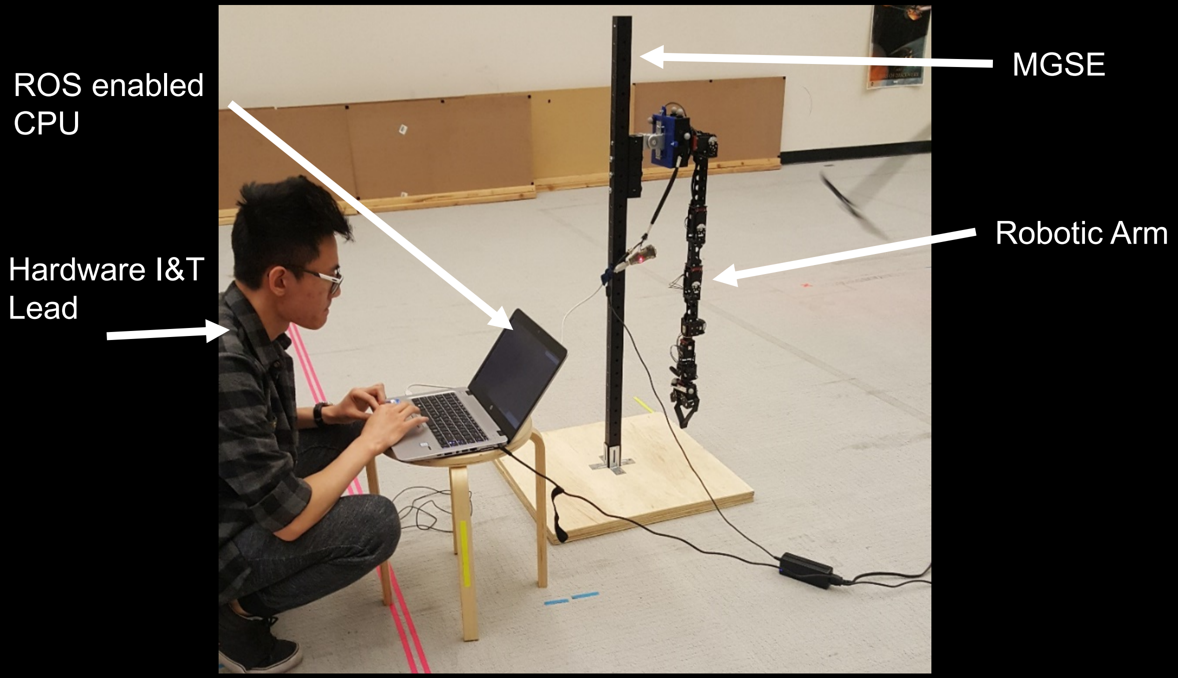


Fig. 18 Robotic Arm Checkout Test set-up.

Procedure:

1. Pass simulated target to MoveIt!
2. Follow generated path
3. Verify actuators did not enter alarm mode

Measured Data:

Binary check of entering alarm mode. (over-torque and temperature exceeding 80C)

System Integration

Test Overview

Visual Processing & Controls Integration

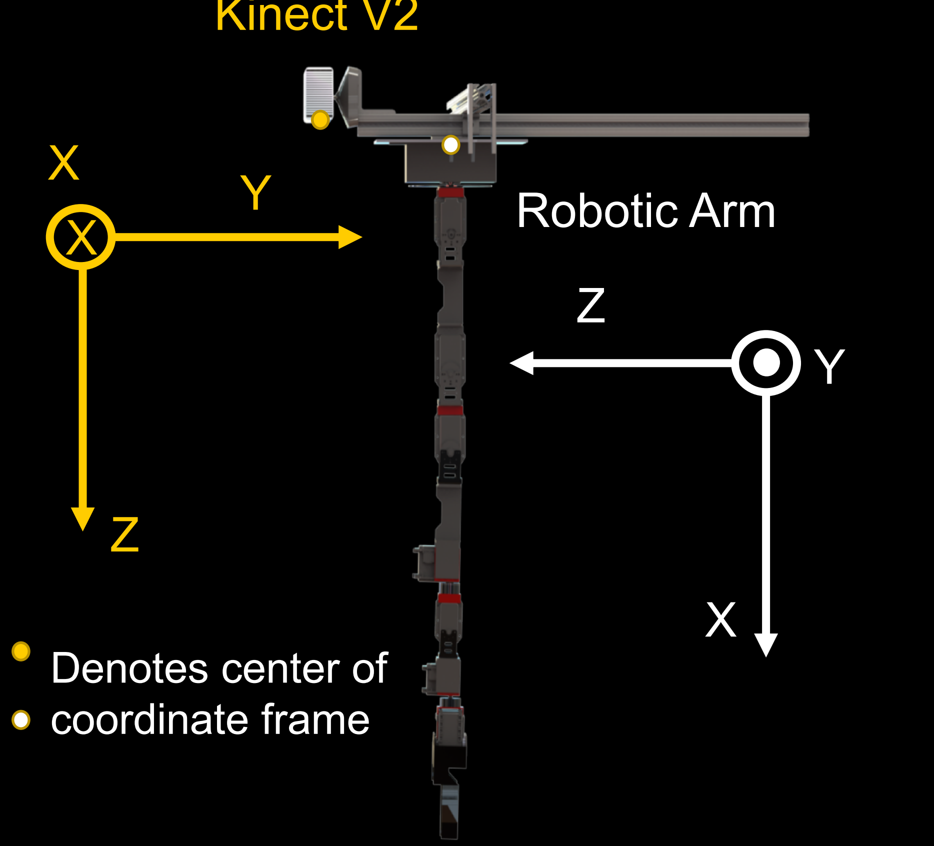


Fig. 19 Kinect V2 and Robotic Arm Reference Frame

- Convert Kinect frame to arm frame with DCM
  - $\Psi = \pi/2$ rad
  - $\Theta = -\pi/2$ rad
  - $\Phi = 0$ rad
- Must account for physical distance between Kinect center and arm center
  - X offset = 0 cm
  - Y offset = -4.873 cm
  - Z offset = 22.77 cm
- Output visual processing data is now centered at arm base in arm coordinate frame

Visual Processing & Controls Integration

Kinect V2 MATLAB toolbox not supported in Linux (ROS platform)

- Challenges
  - Calibration of Kinect V2 in ROS to overlay RGB on point cloud
    - Automatically done in MATLAB
  - Transformation matrix rotations
  - Additional physical offsets needed in Linux than in MATLAB
  - Difficult to debug visual code in full integration

All visual processing algorithms developed through MATLAB (windows) prior to integration.

System Integration: Timing

F4.0 - KESSLER shall have a total mission time no greater than 53 minutes, based off the average LEO orbital period

- One end-to-end operation must be executed in less than 17 minutes
  - Within one mission phase three attempts will be made (2 must succeed)

Prior to Integration	Initial Integration	Optimized Integration
• Visual Processing not yet integrated to ROS • **End-to-End operation: ~5min**	• Continuous data streaming from Kinect V2 (24 MB/s) • **End-to-End operation: 11min**	• Execute a single image capture (RGB & IR) • **End-to-End operation: 3.5min**

Final Integration Test Overview

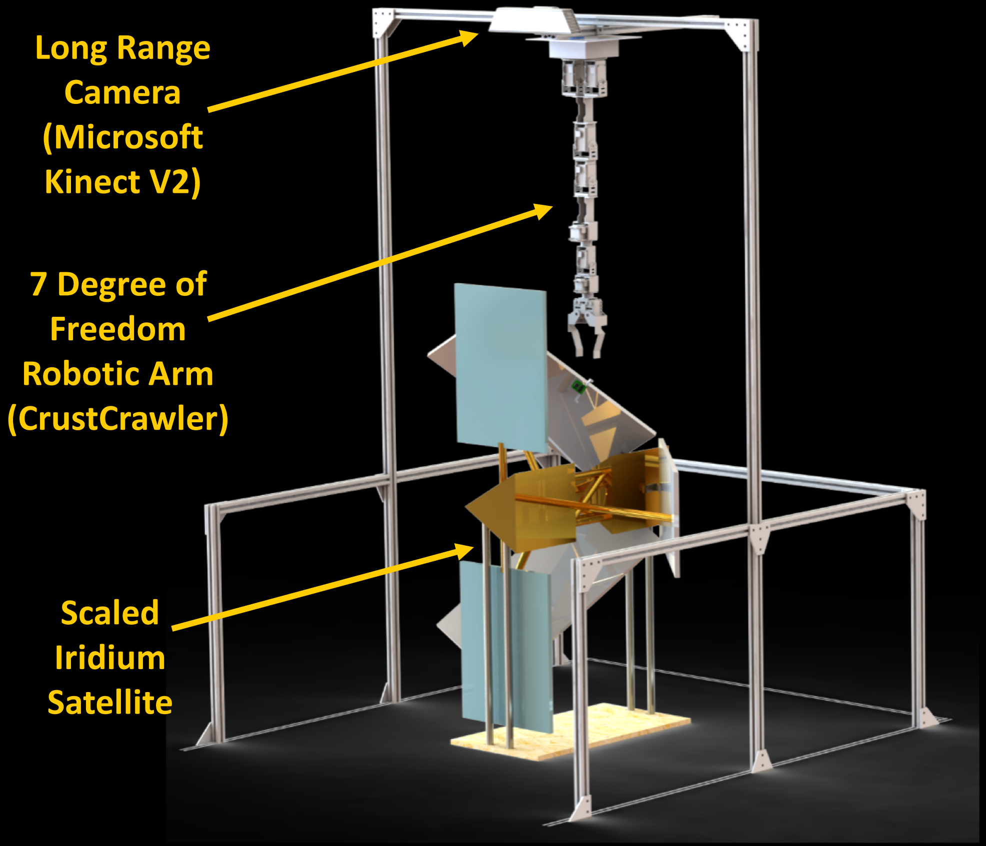


Fig. 20 Kinect V2 and Robotic Arm Reference Frame

Facility:

- Vicon Laboratory

Equipment:

- 2 MGSEs (Robotic Arm, Scaled Iridium Satellite)
- 7 DOF Robotic Arm
- Computer
- Cameras (Microsoft Kinect V2 and ArduCAM Mini)

Special Features:

- Robotic arm suspended in a neutral gravity position
- Lazy Susan aids the manipulation of satellite orientation
- Green Screen below satellite MGSE to mitigate shadow issues

Final Integration Test Overview

Objective: Verify that the Control Subsystem can take inputs from Visual Processing and command the arm

Requirements/Models: D1.4 - The visual system shall be capable of communicating with the control system

D3.2 Final position and orientation of end-effector shall have a total system error no greater than 2 inches and 10 degrees.

D5.1 – The KESSLER system shall have an individual operation time duration of 17 +/- 2 minutes

Equipment/Facilities: VICON Laboratory, Integrated Robotic Arm, Scaled Iridium Satellite, 2X MGSEs, Lighting Mechanism

Measurement Method
Visual Processing
VICON system
Actuators
Inspection

Measured Data:

- Position of closest point (Level 1)
- Position of closest point of plane and Orientation of plane (Level 2,3)
- Final Position and Orientation of End Effector
- Torque of Claw upon securing target (Level 2, 3)
- Time of Operation
- Did the claw secure the satellite without damaging it?

} Difference between Visual and VICON values is total system error

Final Integration Test Setup

Fig. 21 Final Integration Test demonstrating feature capture.

Facility:

- Vicon Laboratory

Procedure:

1. Setup KESSLER System
2. Calibrate VICON via Wand
3. Position Markers on End Effector
4. Run Demonstration
5. Record Test Outputs

Special Features:

- Position/Orientation of End-Effector
- Position/Orientation of Feature
- Torque Measurement of Claw

Test Results

Visual Processing

Test Results

Define Closest Point on Planes Test Results

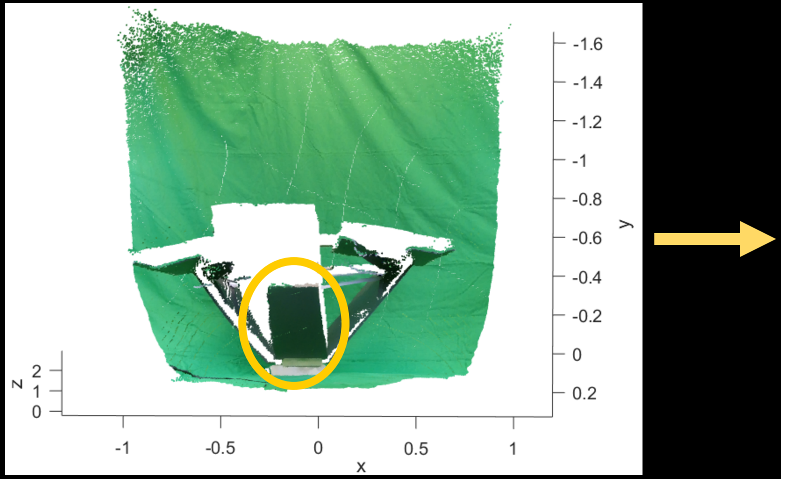


Fig 22: 3D point cloud of satellite model

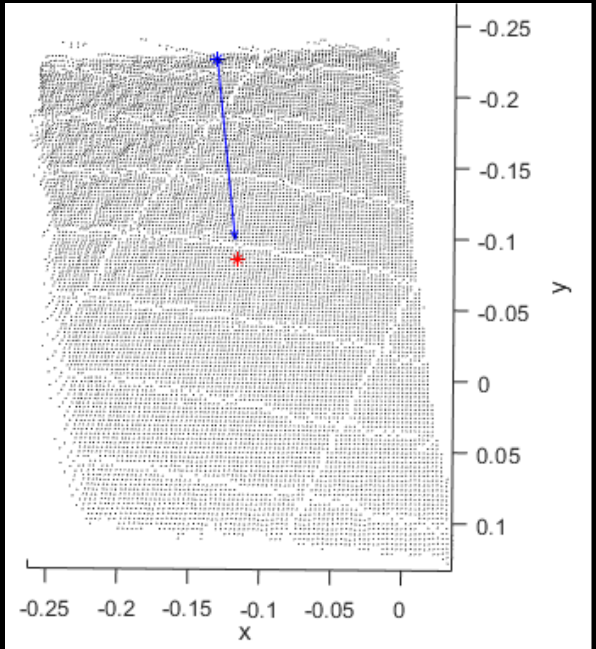


Fig 23: 3D point cloud of isolated plane with closest pt and robotic arm approach angle

- Results
  - Can isolate a plane from the Kinect point cloud
  - Output of closest point to camera
  - Defining orientation with vector betweencapture point and center of plane

Project Overview | Design Description | Test Overview | **Test Results** | Systems Engineering | Project Management

Closest Point on Plane Model Validation

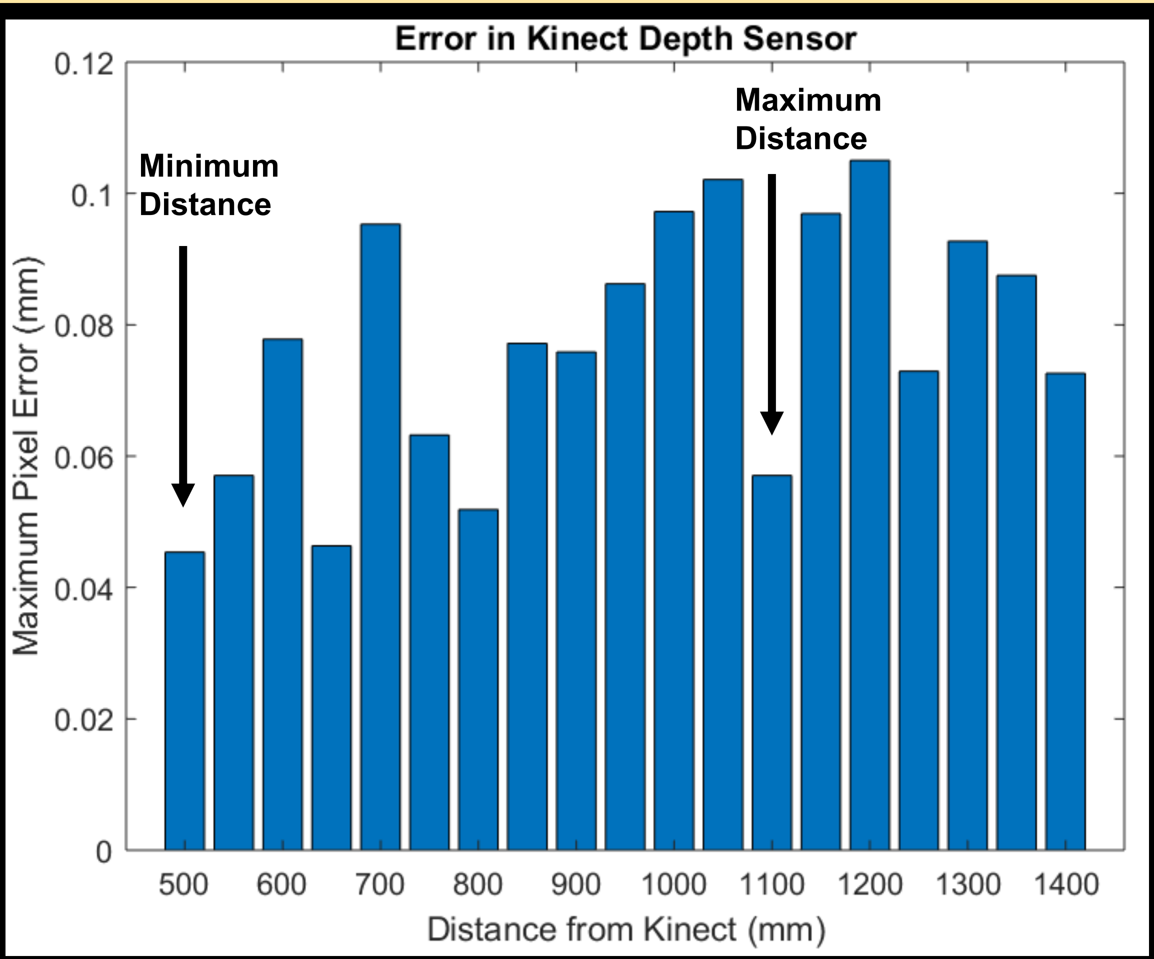


Fig. 24 Depth Sensor error is below the maximum error.

- Maximum error is 0.1 mm
- Error tested at distances greater than those expected during nominal operation

Controls

Test Results

Motion Constraints Test Results

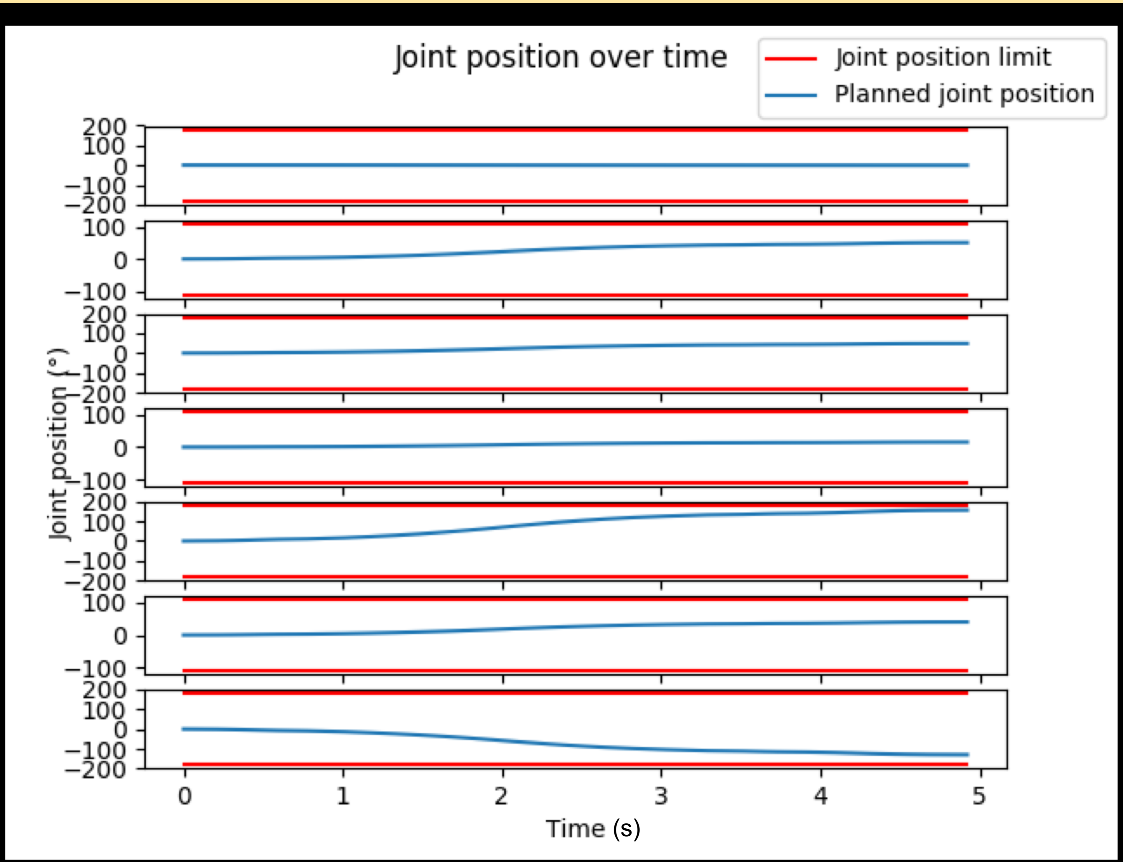


Fig. 25 Commanded joint positions stay within required bounds for 7 joints.

- Results
  - Limits successfully obeyed
  - MoveIt! meets requirement to within 2 degrees from nominal
  - Location error negligible
- Velocity vs. Time investigated
- Status: Complete
- **Validation**: Arm Joint Test

Arm Joint Test Results

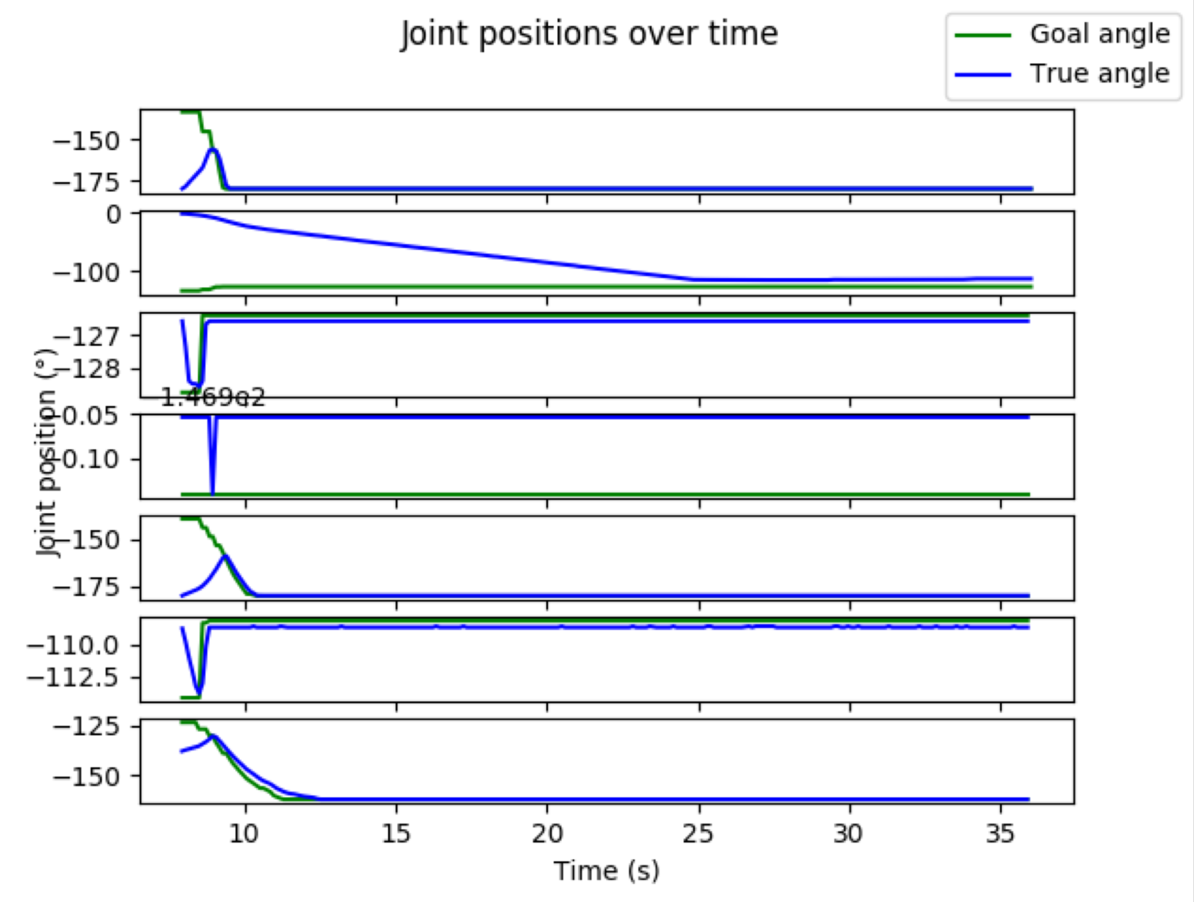


Fig. 26 Initial joint position test results.

- Results
  - Can command actuators in sync
  - Time to reach target errors bear investigation
  - Errors extrapolate to **~23** mm position error
- Status: Complete
- **Validation**: Encoder values incrementally checked to path provided by MoveIt!

Robotic Arm

Test Results

Robotic Arm Checkout Results

Preliminary Test Conducted on 03/23 FAILED

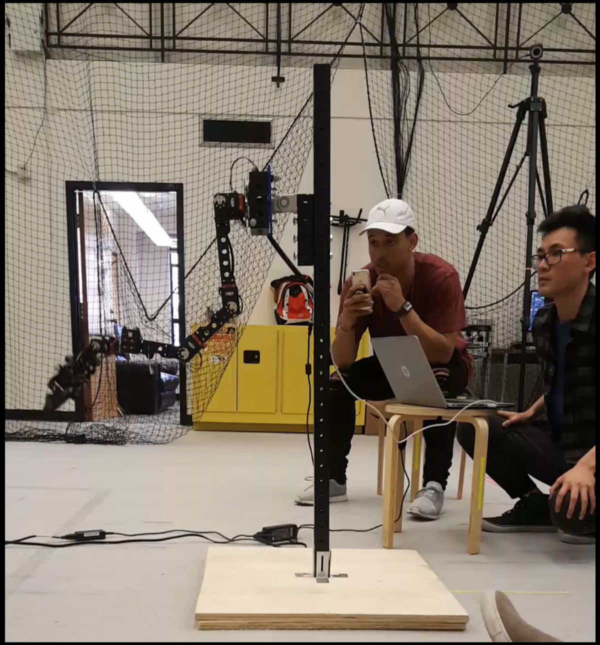


Fig. 27: Robotic Arm Checkout Test attempt 1.

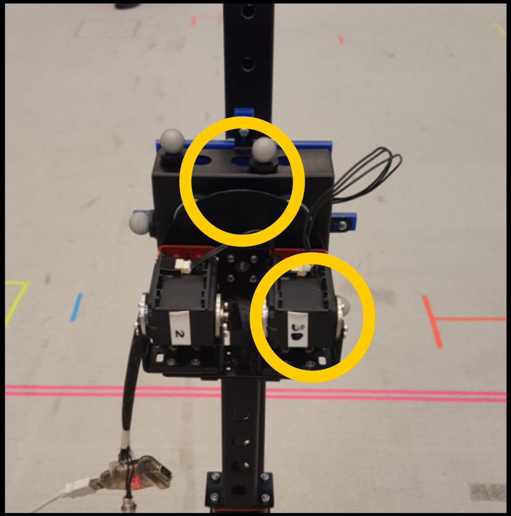
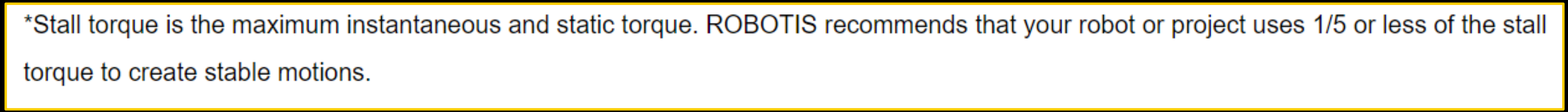


Fig. 28: Actuator 1 and 2&3 (DA) failed.

- Designed FOS was above 1.5 which provided confidence in design.
- After further investigation manufacturer recommends operation FOS closer to 5. (not all datasheets showed this recommendation)

Actuator 1 FOS	Actuator DA FOS
1.6	1.7



*Stall torque is the maximum instantaneous and static torque. ROBOTIS recommends that your robot or project uses 1/5 or less of the stall torque to create stable motions.

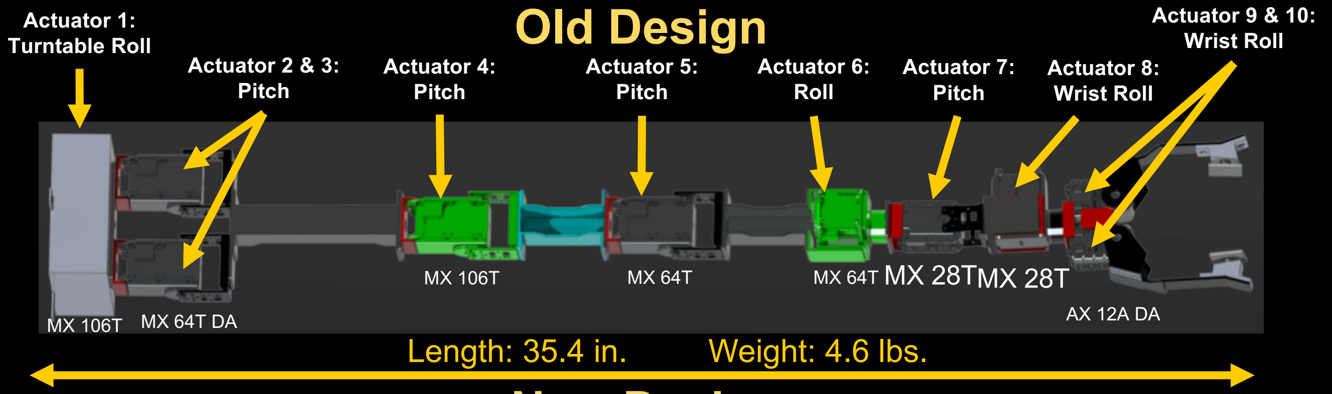
Comment from manufacturer

Robotic Arm Checkout - Rework

- Steps Taken:
  - Replace Dual Actuators (2 & 3) with higher torque
  - Shorten arm by ~5 inches
  - Suspend arm to remove gravitational load on turn table
- Implications on system
  - Full MGSE redesign
  - Visual processing database required to be recreated with ‘top down’ view of satellite

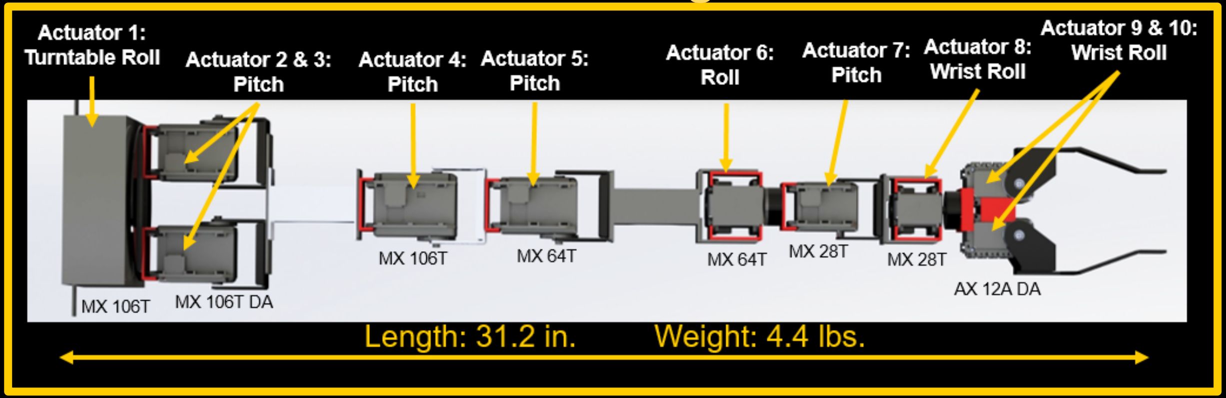
This was all done in 1.2 weeks (starting in Saturday 03/24)

Old Design



Length: 35.4 in. Weight: 4.6 lbs.

New Design



Length: 31.2 in. Weight: 4.4 lbs.

Actuator 1 FOS	Actuator DA FOS
2.8	5.5

Robotic Arm Checkout Test Results

Fig. 29: Suspended Configuration.

Tested Robotic Arm with shortened length

Proved to be successful

Tested Robotic Arm with high torque actuators.

Proved to be successful

These results meet the pass the test criteria for RA checkout.

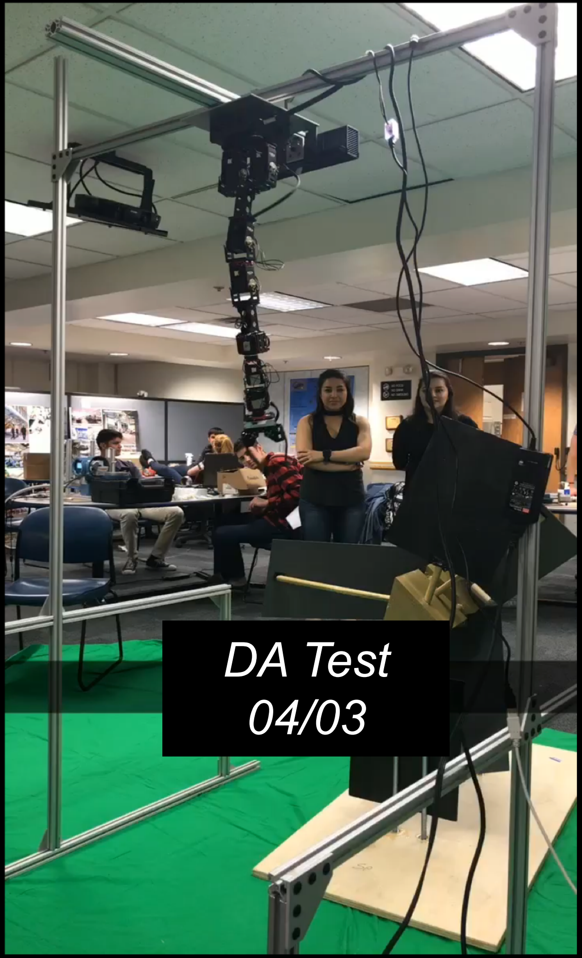


Fig. 30: Suspended and new actuators.

System Integration

Test Results

Final Integration Results

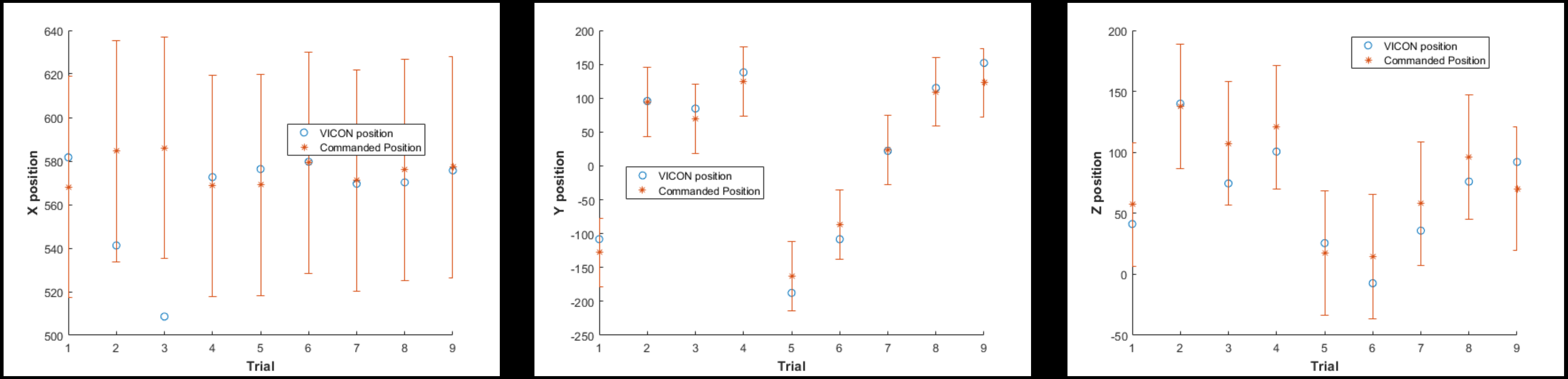


Fig. 31: Integrated position vs. Truth Data from VICON in every dimension

- Final Level 1 Integration confirmed that Visual and Controls were integrated
- Test was conducted on April 16th. Trial runs were taken after transformation matrices and offsets were fine tuned
- Controls Checkout was done during integration tests by using the point from visual as the point to which controls would navigate to
- Final Allowable Error was 2 inches (50.8 mm), a range represented by the red error bars
- For all trials except trial 3 in the x position, requirements were met

Final Integration Results

- Average error was 32 mm, <u>below</u> our 2 inch (50.8 mm) requirement
- 8 out of 9 trials were successful, leading to an over 90% certainty that we met or exceeded our 66% success rate requirement
- Predicted error in TRR, assuming that error would be a result of the cumulative visual and controls errors was 0.72 inches (18.3 mm)
- Higher than predicted error was caused by lingering imperfections in the transformation matrices and offsets
- Test confirmed that our Level 1 Requirement of navigation the end effector to the closest point on the satellite was met

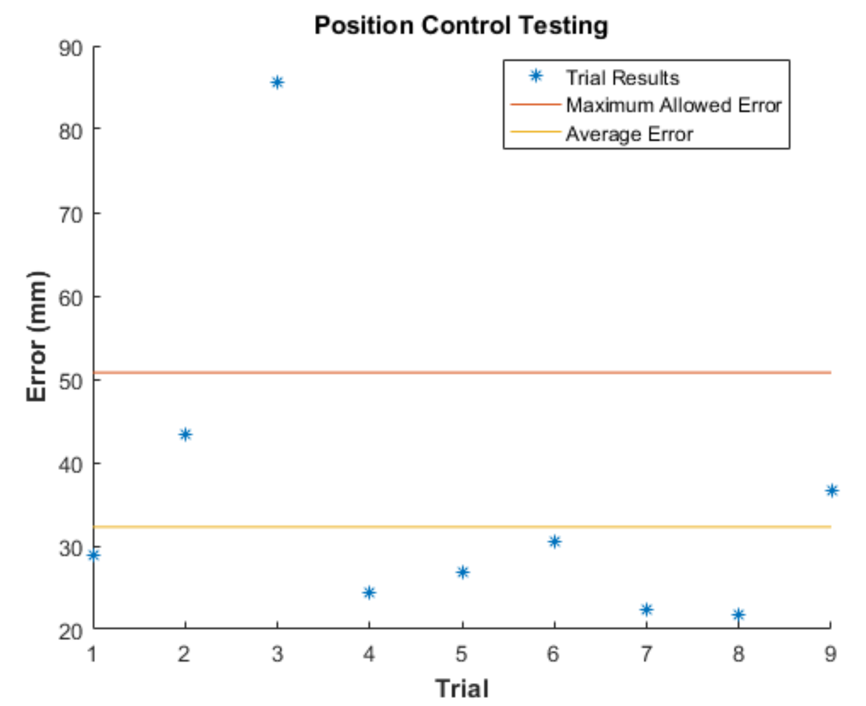


Fig. 32: Total error in integrated position vs. Truth Data from VICON

Final Integration Results

- Level 2 required final orientation to be within 10 degrees
- Average errors were:
  - 4.94 degrees in the roll
  - 12.50 degrees in the yaw
  - 11.67 degrees in the pitch
- Roll was the only result that consistently met the requirement
- As of April 16th partial Level 2 success has been achieved.
  - System is able to autonomously capture predetermined satellite feature
  - Orientation exceeds required error bounds in two of three Euler angles

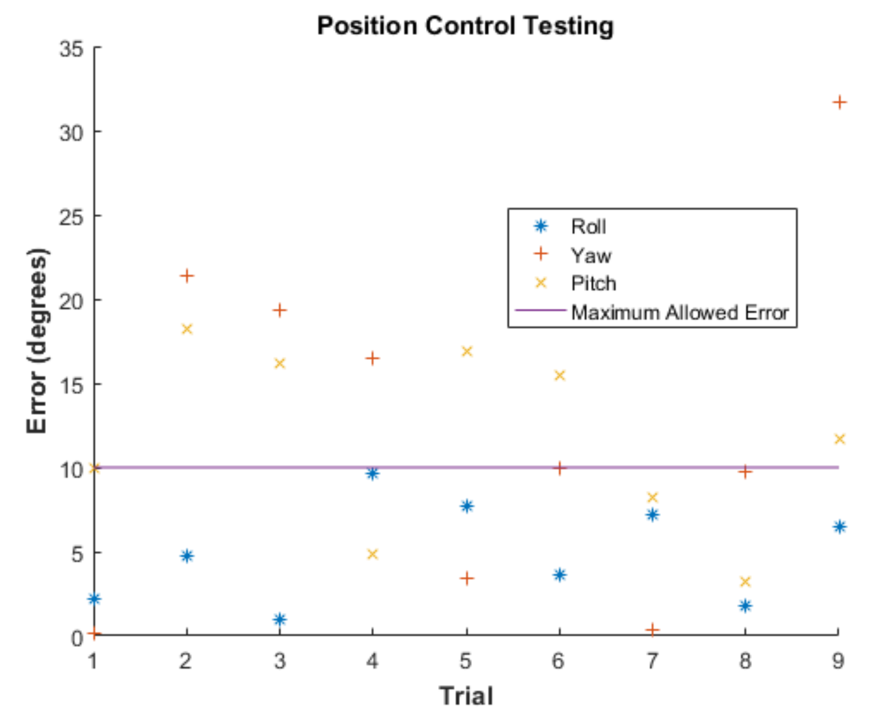


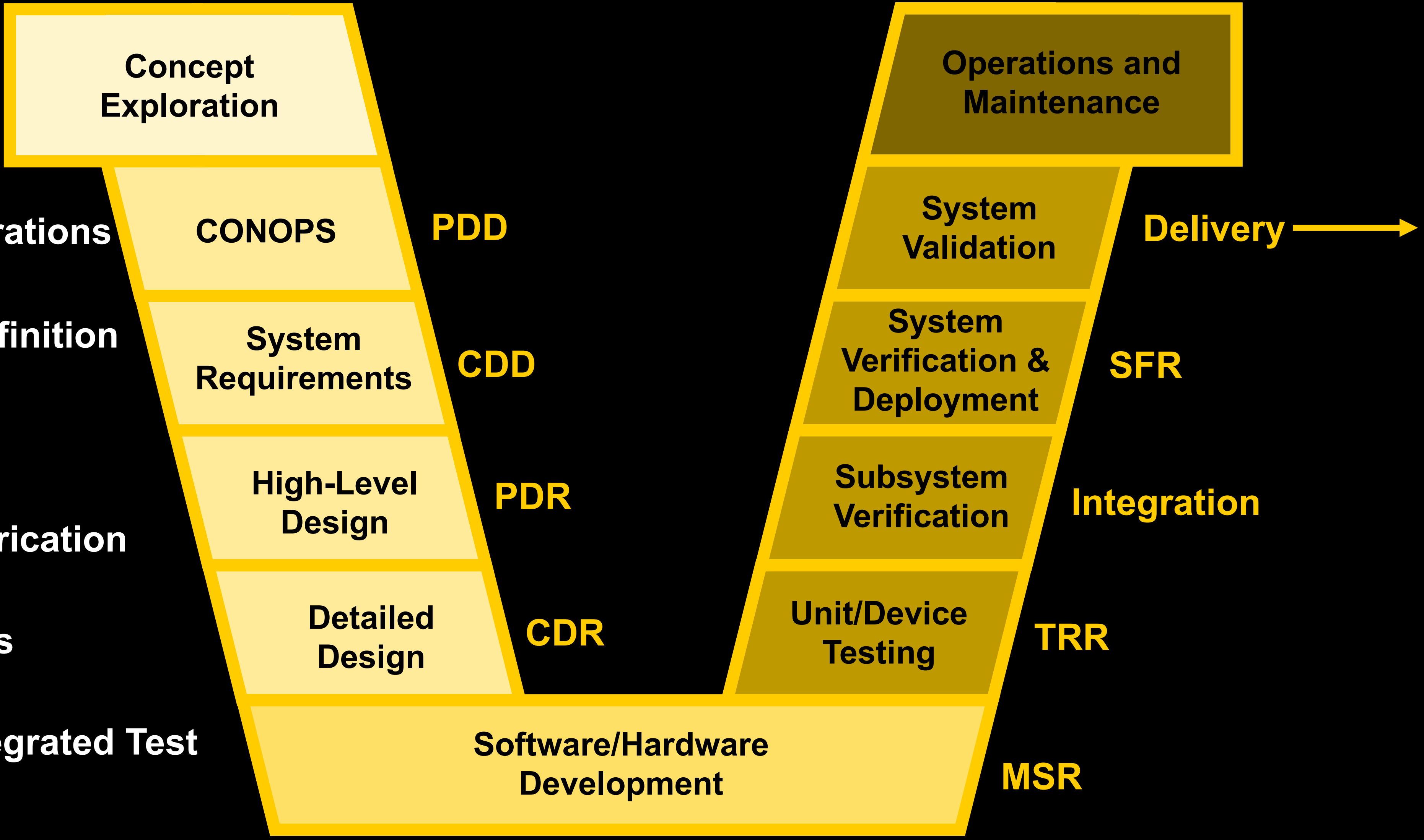
Fig. 33: Errors in Rotation angle between Arm and VICON

Project Overview | Design Description | Test Overview | **Test Results** | Systems Engineering | Project Management

Systems Engineering

Systems Engineering V

Concept of Operations
↓
Requirement Definition
↓
Detailed Design
↓
Component Fabrication
↓
Subsystem Tests
↓
Full System Integrated Test



Concept Exploration

CONOPS — PDD

System Requirements — CDD

High-Level Design — PDR

Detailed Design — CDR

Software/Hardware Development — MSR

Unit/Device Testing — TRR

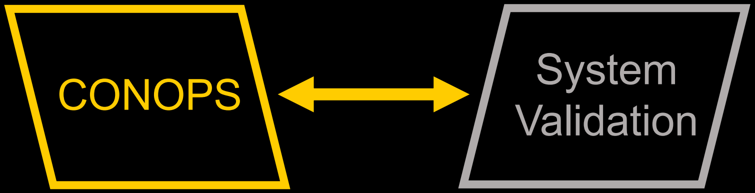
Subsystem Verification — Integration

System Verification & Deployment — SFR

System Validation — Delivery →

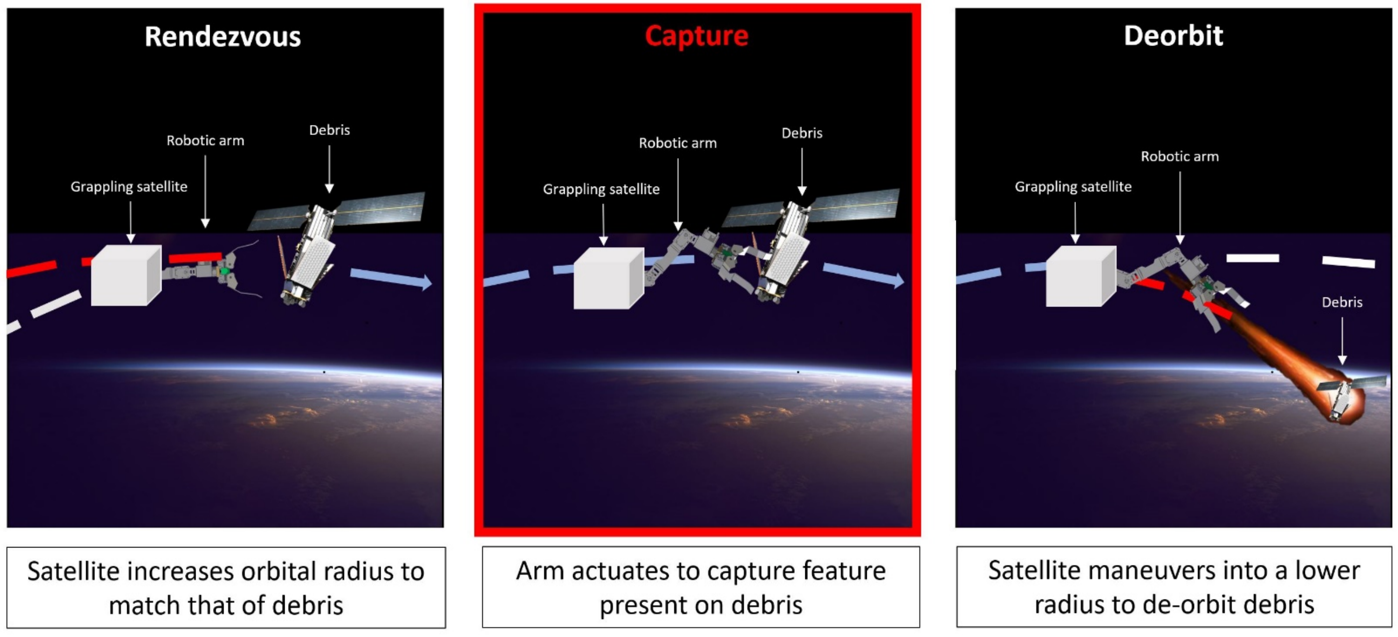
Operations and Maintenance

Systems Engineering Approach


CONOPS

System Validation

Concept of Operations



Satellite increases orbital radius to match that of debris

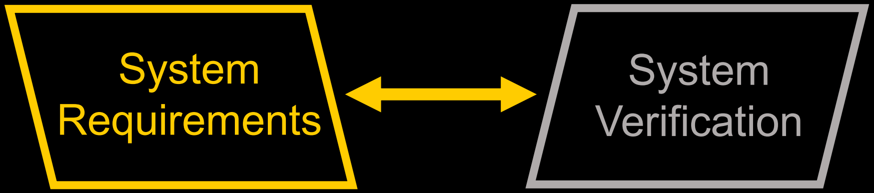
Arm actuates to capture feature present on debris

Satellite maneuvers into a lower radius to de-orbit debris

Lessons Learned:

- Well defined scope by customer
- Enabled development of requirements that are feasible to verify and validate

System Engineering Approach



Requirement Definition

O1: Take visual data (via picture) confirming the target object (satellite) is in KESSLER's Field of View (FOV)

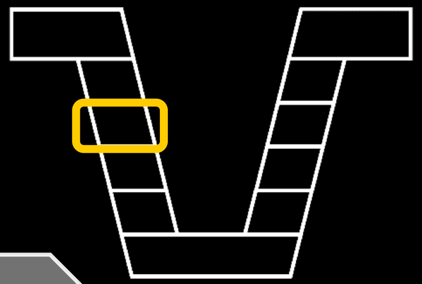
O2: Identify pre-selected satellite features (PGF's) on the target object which has an unknown position and orientation

O3: Determine a path to PGF(s)

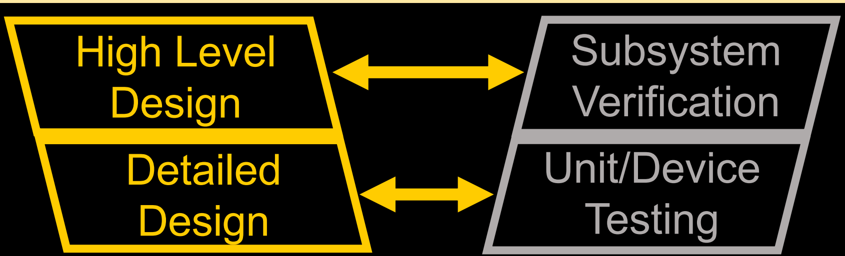
O4: Autonomously capture the PGF(s) on the target object via the robotic arm

Lessons Learned:

- Well defined requirements lead to fluidity later in the project
- Main driver for design developments
- Communication with customer is key



System Engineering Approach



Detailed Design

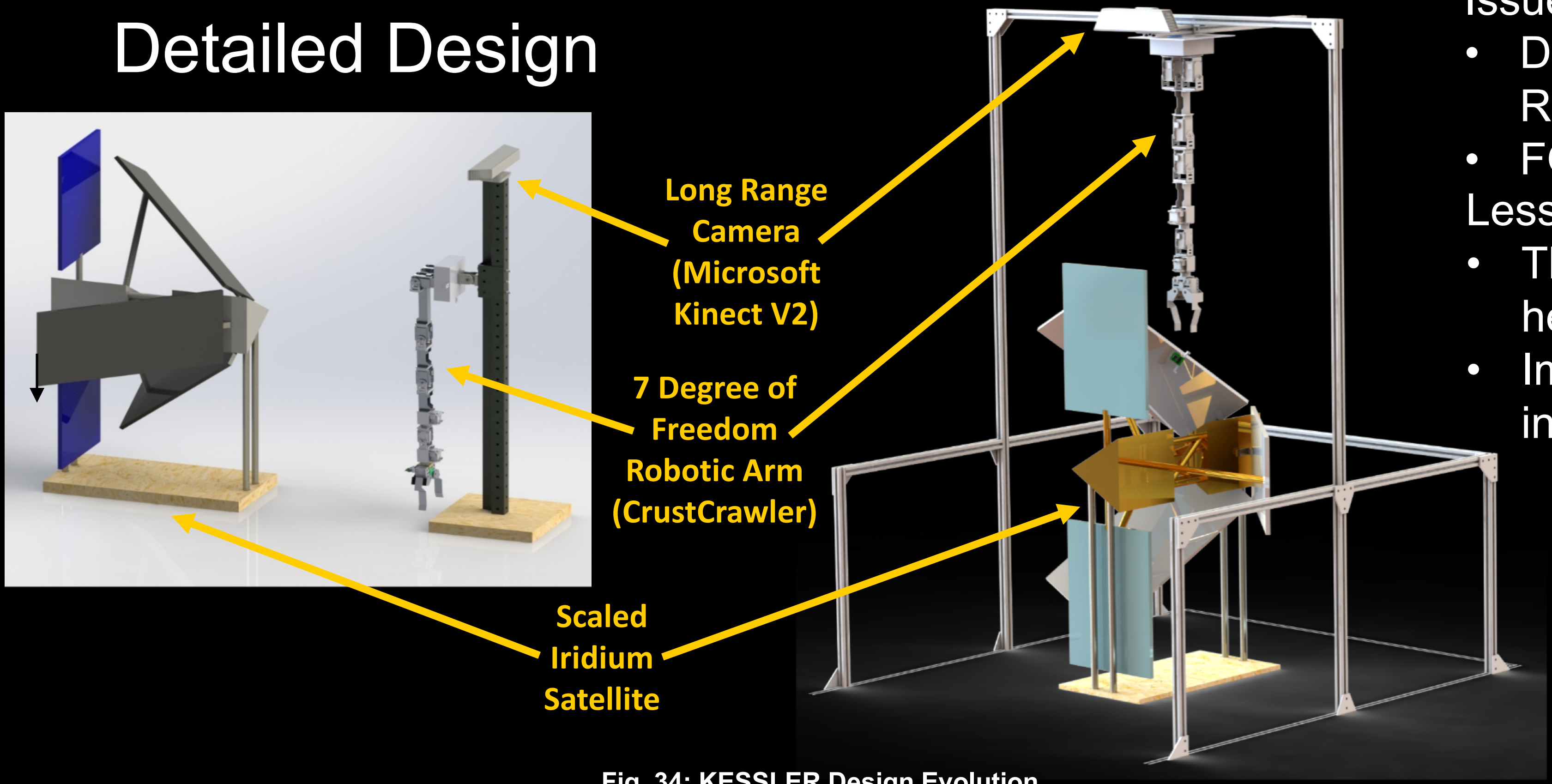


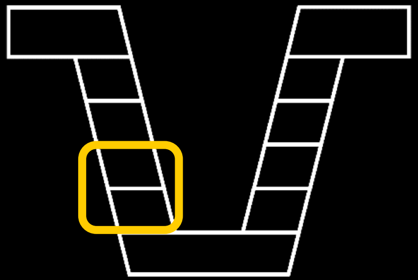
Fig. 34: KESSLER Design Evolution

Issues:

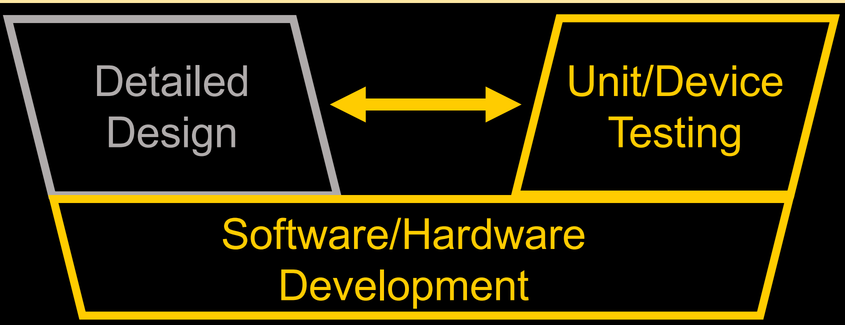
- De-integration issues due to Red Loctite
- FOS Recommendation

Lessons Learned:

- Thorough knowledge of heritage hardware
- Importance of spec sheet inspection



System Engineering Approach

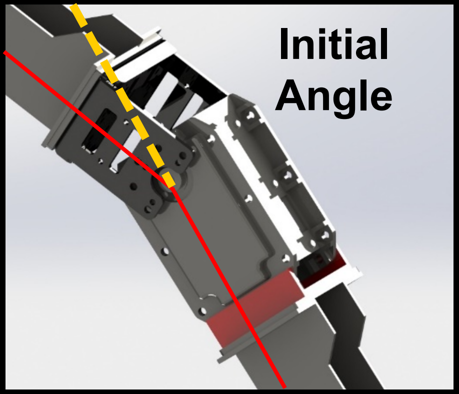


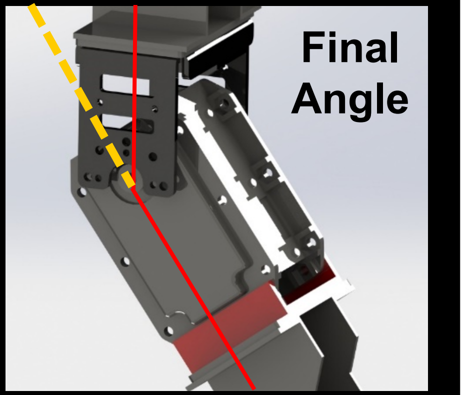
Detailed Design

Unit/Device Testing

Software/Hardware Development

Component Fabrication





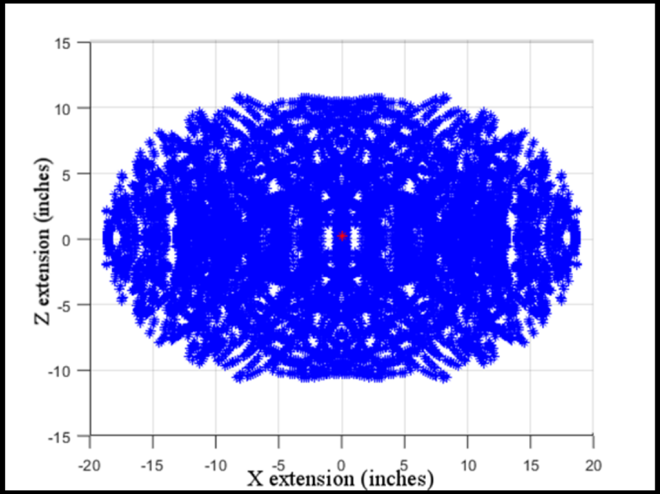


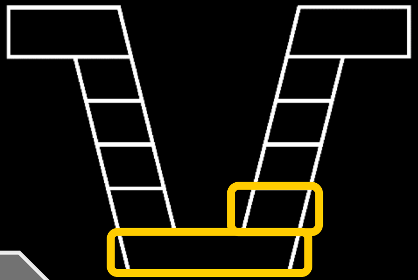
Fig. 35: Design Verification (Workspace Analysis)

Issues:

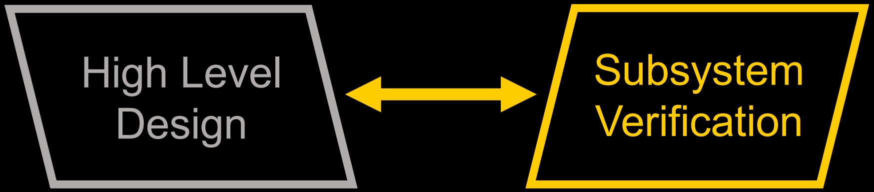
- Schedule slip due to procurement delay

Lessons Learned:

- Technical developments to be done in parallel



System Engineering Approach



High Level Design

Subsystem Verification

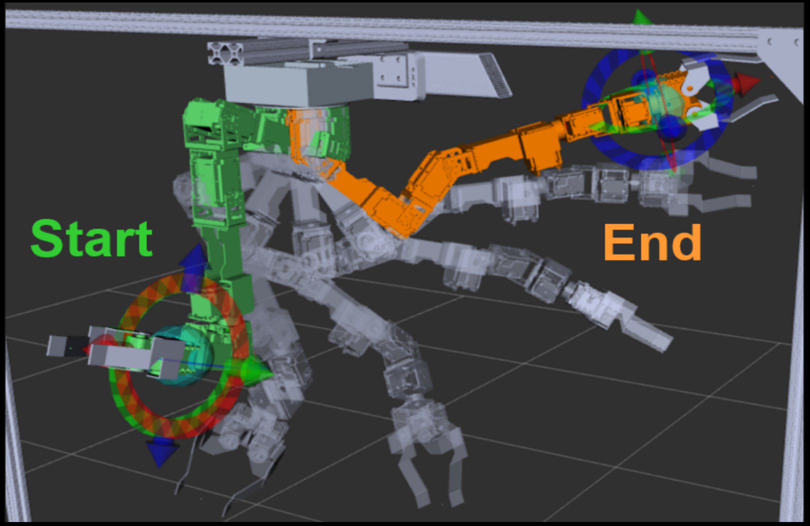
Issues:

- Difficulties with plane detection
- Failure of actuators while in config.
- Higher FOS on actuators required

Lessons Learned:

- Image capture crucial for VP
- Need for stronger actuators
- Need for a gravity neutral MGSE
- Time and funds to be biggest risk mitigator

Subsystem Tests



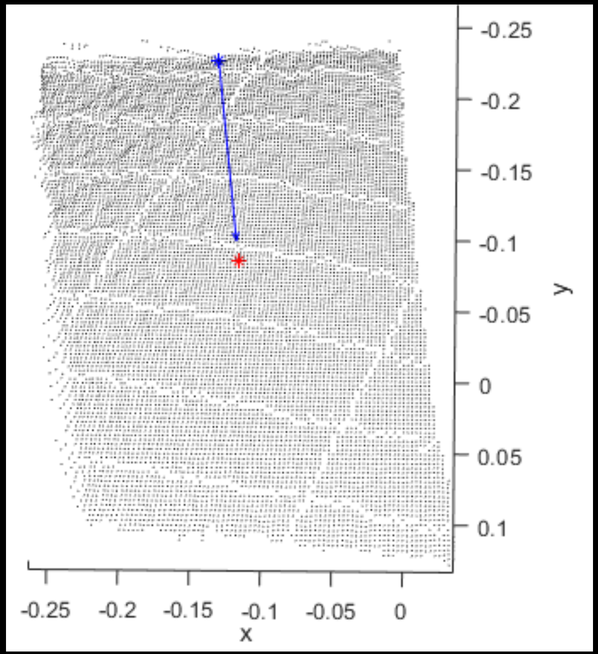
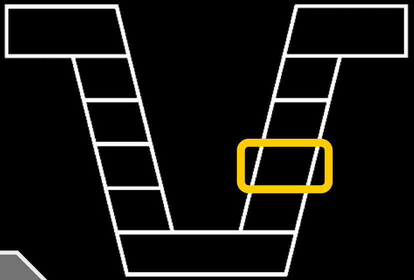
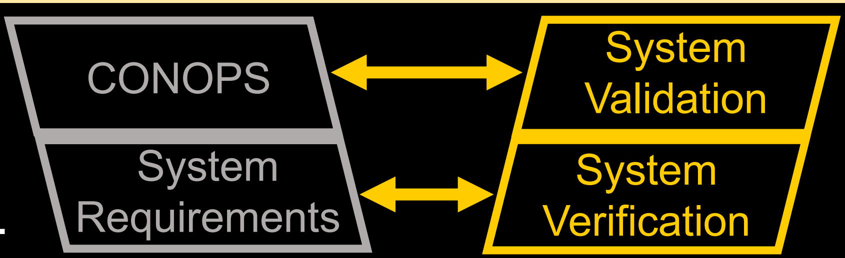


Fig. 36: Controls (left) and Visual Processing (right) verification



System Engineering Approach



Full System Test

Fig. 37: Full System Integrated Testing

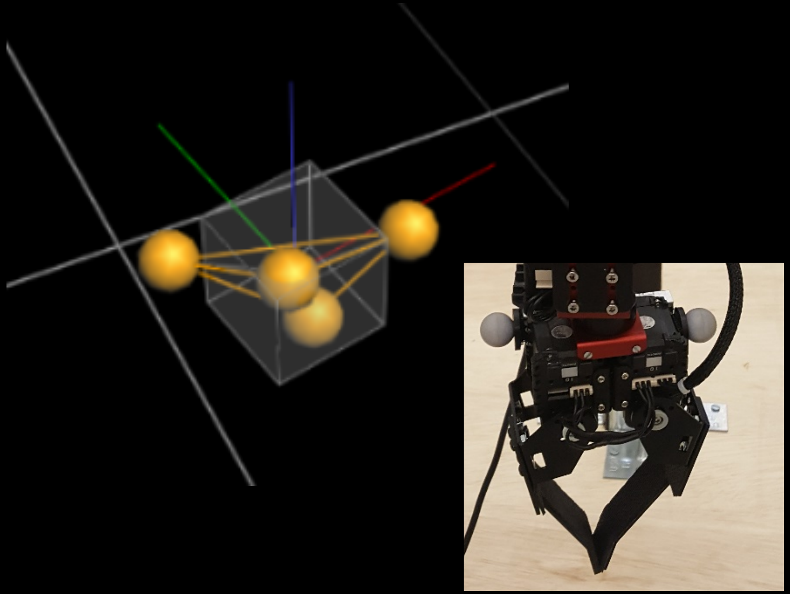
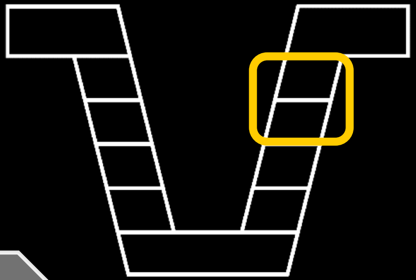


Fig. 38: End-Effector object definition via Vicon Cameras (pearl markers)

Issues:
- Difficulty of transformation matrix
- Complication with Linux integration

Lessons Learned:
- Doublecheck manufacturer assumptions about coordinate frames
- Development of both algorithms in ROS
- Communication among subsystems is crucial



Key Trades

Integration of Software

Rationale

- No use of heritage software
- Powerful platform for robotics with various features

Implications

- Nontrivial learning curve
- Ease of algorithm integration

Hardware Lifetime

Rationale

- Unknown status of heritage hardware
- Differing FOS requirement of design than CASCADE

Implications

- Schedule slip
- Reallocation of budget

Project Management

Project Management Approach

Prior to Project Bazaar

- Contacted peers from previous labs
- Voted on highest technical interests
- Conducted skill survey

Team Dynamic & Skill Versatility >> Project Topic

Post Project Selection

- Sub-milestone definition with Team Buy-In
- Weekly reviews with advisor and customer

‘Milestone Driven’ PM Approach based on Course Structure

Fall 2017

- Subsystem design reviews leading into course reviews
- Reviewed by customer, advisor and some PAB

Subsystem Autonomy with PM & SE collaborative oversight.

Spring 2018

- Multiple subsystem working hours
- 4-8 hour shifts with ~7/11 team members present

All hands on deck as we approached integration efforts.

Presentation ‘content reviews’ held Thursdays prior to Monday submissions. Upon feedback received we met with PAB to help rectify / clarify any issues.

Project Overview
Design Description
Test Overview
Test Results
Systems Engineering
Project Management

Project Management Success

- Team Dynamic
  - Adaptive and versatile to unexpected technical issues
  - Always had a positive attitude
- Full Level 1 and Partial Level 2 Success met
- AIAA Student Conference Win
  - Acquired travel funds for 10 team members

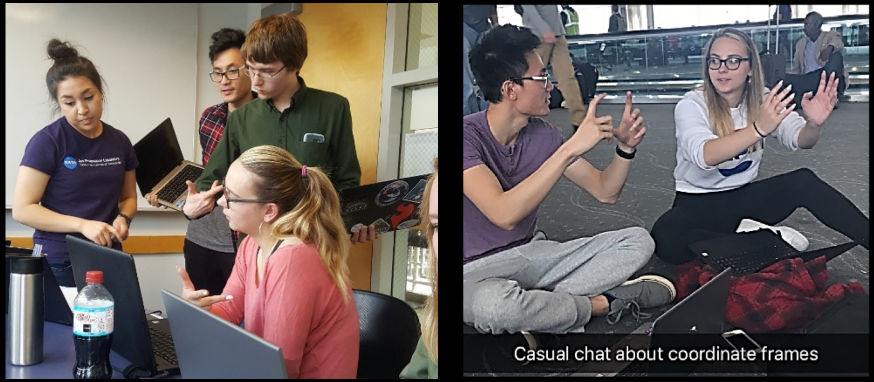


Fig. 40: KESSLER Team Technical Discussion

AIAA FOUNDATION
Advancing Aerospace

REGION V STUDENT PAPER CONFERENCE

Sponsored by Lockheed Martin Corporation

LOCKHEED MARTIN

Lauren Darling, Abdiel Agramonte-Moreno, Glenda Alvarenga, Cong Bui, Christopher Choate, Sergey Derevyanko, Cassidy Hawthorne, Abigail Johnson, Nick Thurmes, Jannine Vela

Third

Team

Presentation of Technical Paper

A Commercial Imaging and Robotics System for Satellite Space Servicing
April 2018

James G. Maser
AIAA President

Daniel L. Dumbacher
AIAA Foundation President

Fig. 39: KESSLER Team AIAA Region V Student Conference Win

Fig. 41: KESSLER Team Chili Cook-Off

Project Overview → Design Description → Test Overview → Test Results → Systems Engineering → **Project Management**

Project Management Difficulties

- Lack of previous coursework in robotics and visual processing
- Actuator supplier FOS specification vs recommendation
- Heritage hardware and Red Loctite
  - Customizing the previous hardware was very difficult
  - Arm de-integration for actuator testing delayed progress
  - Project expenses increased by 160%
  - Schedule delayed by a total of one month due to unforeseen orders
    - Back-order and shipping delays added more uncertainty
  - Team was required to work over spring break to close the schedule

Lesson learned: Inspect all heritage hardware thoroughly before Spring Semester

Project Overview
Design Description
Test Overview
Test Results
Systems Engineering
Project Management

CDR Cost Plan vs. Actual Cost

CDR Cost Plan

Subsystem	Cost
Visual Processing	$516.00
Mechanical	$757.00
Software Control	$0.00
Ground & Test Support	$675.00
Electrical	$670
Misc	$0.00
% Margin	15%
Total Projected Cost	$3,010

Updated 12/04/2017

Actual Cost

Subsystem	Cost
Visual Processing	$296.24
Mechanical	$3,357.97
Software Control	$0.00
Ground & Test Support	$826.03
Electrical	$236.56
Misc.	$77.98
Total Cost	$4,794.78
Remaining	$205.22 (4.1%)

Updated 4/19/2018

CDR Cost Plan vs. Actual Cost

Planned vs. Actuals Highlighting Primary Drivers of Discrepancy

Subsystem	Percent Difference	Reasoning
Visual Processing	57%	CDR Plan was conservative
Mechanical	444%	Red Loctite, Spring Break Redesign
Software Control	N/A	
Ground & Test Support	122%	Spring Break Redesign
Electrical	35%	CDR Plan was conservative
Total	**159%**	**Biggest Impact was Mechanical Cost Increase**

Red denotes significant cost increase

Project Level of Effort

Industry Equivalent of Project Cost

Item	Cost
Total Labor Cost	$ 146,906.25
Total Overhead	$ 293,812.50
Total Material	$ 4,794.78
Industry Cost	**$ 445,513.53**

Note: Does not account for tax exemption and student discounts obtained for material costs.

- Project Hours – Total: 4701
  - Fall: 2139 Hours
  - Spring: 2562 Hours
- Assuming Labor Hourly Rate: $31.25
  - Starting salary of $65k for 2080 Hours
- Assuming 200% Overhead Rate

Project Overview
Design Description
Test Overview
Test Results
Systems Engineering
Project Management

We would like to thank

- Josh Stamps and Sierra Nevada Corporation (project customer)
- Dr. Jade Morton (project advisor)
- Ann and H.J. Smead Aerospace Engineering Sciences department
- ASEN 4018-4028 Senior Design 2018 Project Advisory Board
- University of Colorado Boulder RECUV RIFLE Lab (high accuracy verification testing support with Vicon)
- Pacific Bells Inc. (project travel financial support)

Thank You

Questions?

BACKUP

Section 1 Backup

Concept of Operations

3. Secondary Positioning

- ArduCam Mini takes secondary images to fine tune position of robotic arm
- Robotic arm actuates to the adjusted position and orientation of the PGF

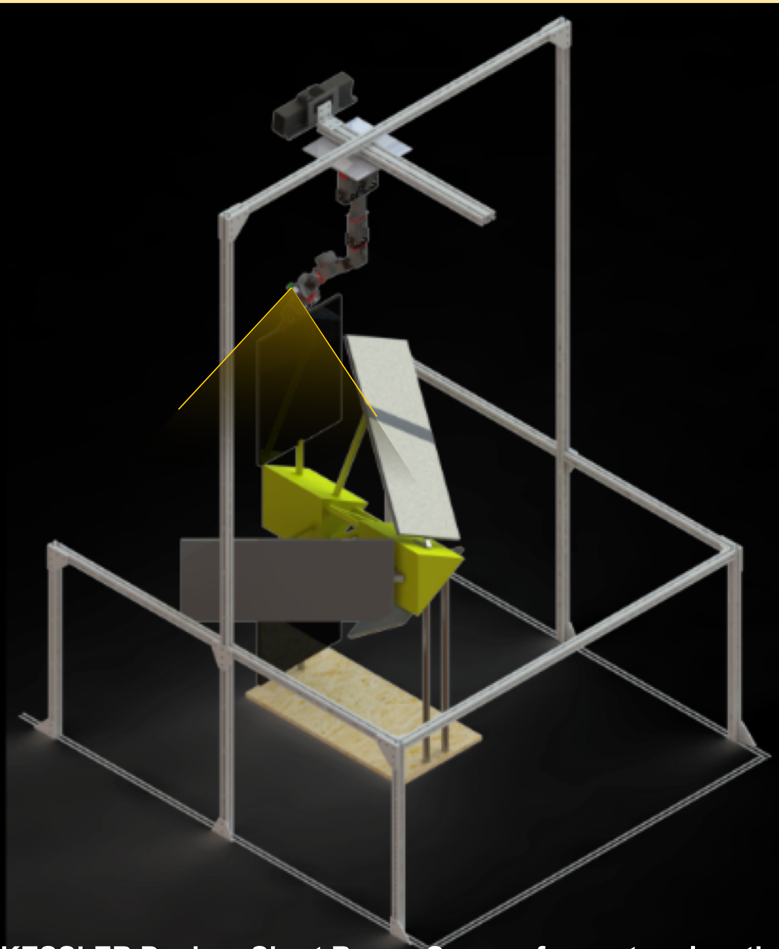
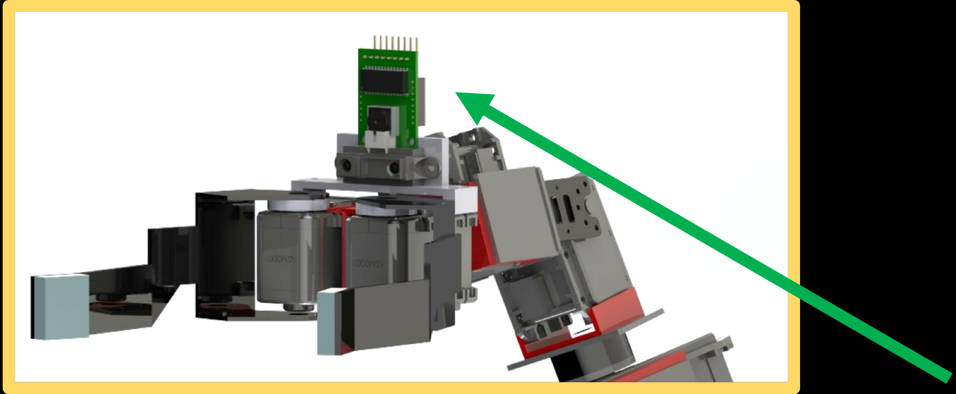


Fig. 7 KESSLER Design: Short Range Camera for capture location fine tuning.



Short Range RGB Camera & Prox Sensor on Robotic Arm Wrist

Project Description

Project Assumptions

- Satellite Position:
  - Object is in front of and within reach of robotic arm.
- Satellite Dynamics:
  - Object is stationary with respect to robotic arm.
- Lighting Conditions:
  - Operations are conducted during Sun-Soak orbital phase.
- Standard Spacecraft Subsystems:
  - Are not in scope of KESSLER project (e.g. ADCS, EPDS, CDH, COM).
- Environment:
  - Controlled test environment at 1G and atmosphere.

All assumptions are approved by project customer.

Project Purpose

- The simulated target satellite is modeled after the Iridium satellite series.
- Model will be 30% scale
- Features are:
  - Solar Panels
  - Bus Structure
  - Antenna
- Features on Iridium are commonly found on other satellites as well.

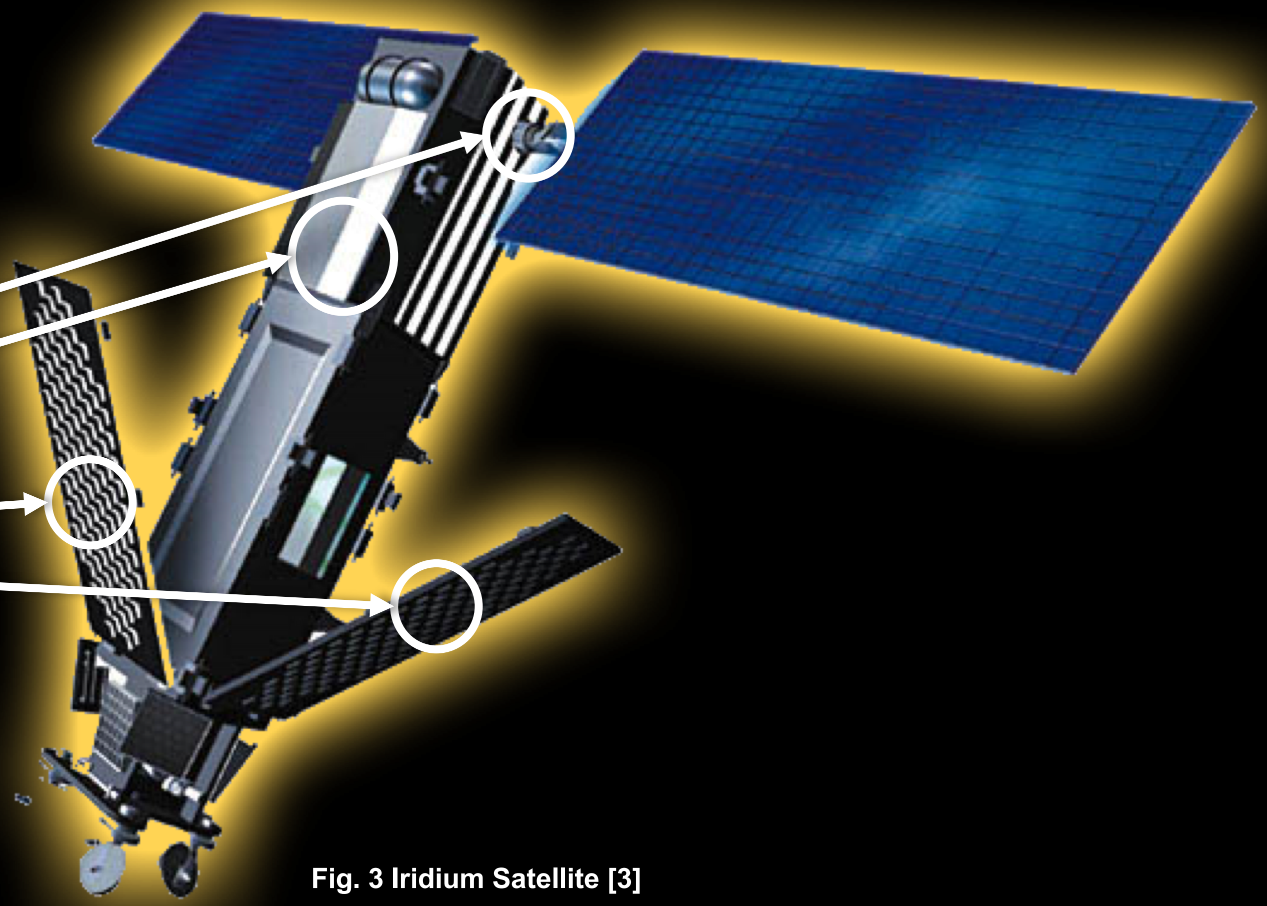


Fig. 3 Iridium Satellite [3]

Level 1 Success Criteria

***Table 1**: Level 1 Success Criteria*

Identification	Processing	Command Execution
Identify at least two surfaces with varying depths in 3D space.	**Identify the distance between the closest point of the satellite and the base of the robotic arm (± 4mm).**	**Demonstrate end-effector can move to closest point and actuate while facing the parallel plane (± 47mm).**

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria

Level 2 Success Criteria

***Table 2**: Level 2 Success Criteria*

Identification	Processing	Command Execution
Identify grappling feature recognition on target satellite.	**Determine grappling feature location and orientation to within ± 4mm & ± 5 degrees.**	**Grapple feature in parallel plane to within ± 90 degree of end-effector roll angle.**

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria

Level 3 Success Criteria

***Table 3**: Level 3 Success Criteria*

Identification	Processing	Command Execution
Identify collision feature on target satellite.	Define keep-out zone to within ± 4mm of collision feature surface, and select grappling feature that causes the smallest collision risk.	Grapple feature in perpendicular plane (demonstrate additional Degree of Freedom).

*Three categories decoupled to ensure there is no dependency when meeting mission success criteria

Design Functionality

Project Assumptions

#	**Description**
1	Target object is in-front & within reach of the robotic arm; this entails that this scenario is valid if the target object and the chase vehicle are in the same orbit and in proximity to each other.
2	Target object is stationary with respect to the chase vehicle (robotic arm base plate); this entails that this scenario is valid (in an orbital case)if the target object is 3-axis stabilized (or the chase vehicle has matched rotation at one axis if 2-axis stabilized).
3	Chase vehicle operations (target and capture) occurs during Sun-soak in an average Lower Earth Orbit (LEO); this entails that lighting conditions are not in the scope of KESSLER.
4	KESSLER mission will be demonstrated in a controlled test environment (1G & atmosphere).
5	KESSLER will not design the "chase vehicle's" system; this entails that electrical power system, command & data handling, attitude determination & control, etc. will not be in the scope of the KESSLER project.
6	Main characteristics of the KESSLER mission include antennas, solar panel joints, and bus structure supports.

Design Functionality

Functional Requirements

Req. ID	**Requirement**	**Verification Method**
F1	The **visual processing algorithm** shall identify the surface of a satellite in the primary camera's (RGB) field of view (FOV) and within the robotic arm's reach.	Imaging Analysis & Visual Inspection
F2	Control **algorithm** shall **define a path** to the location of a grappling feature.	Path Simulation (Experimental vs. Theoretical Location)
F3	Robotic arm shall **autonomously navigate** to at least one preselected grappling feature on the satellite.	Demonstration/Test
F4	The KESSLER system shall have a **total mission** time no greater than **53 minutes.**	Timing Analysis
F5	KESSLER shall **execute** a total of **3 end to end process operations** and succeed at least twice within the total mission time.	Demonstration/Test

Design Requirements

REF ID	Description	Verification Method
D1.1	The visual processing algorithm shall be capable of detecting a feature at a minimum distance of 20 inches.	Demonstration/Test
D1.2	The visual processing algorithm shall be capable of identifying the main characteristics of a satellite with a level of confidence greater than or equal to 75%.	Image Analysis
D1.3	The visual processing algorithm shall identify the position (x,y,z) and orientation (Euler angles) of an object in 3D space.	Image Analysis
D1.4	The visual system shall be capable of communicating with the control system.	Demonstration/Test

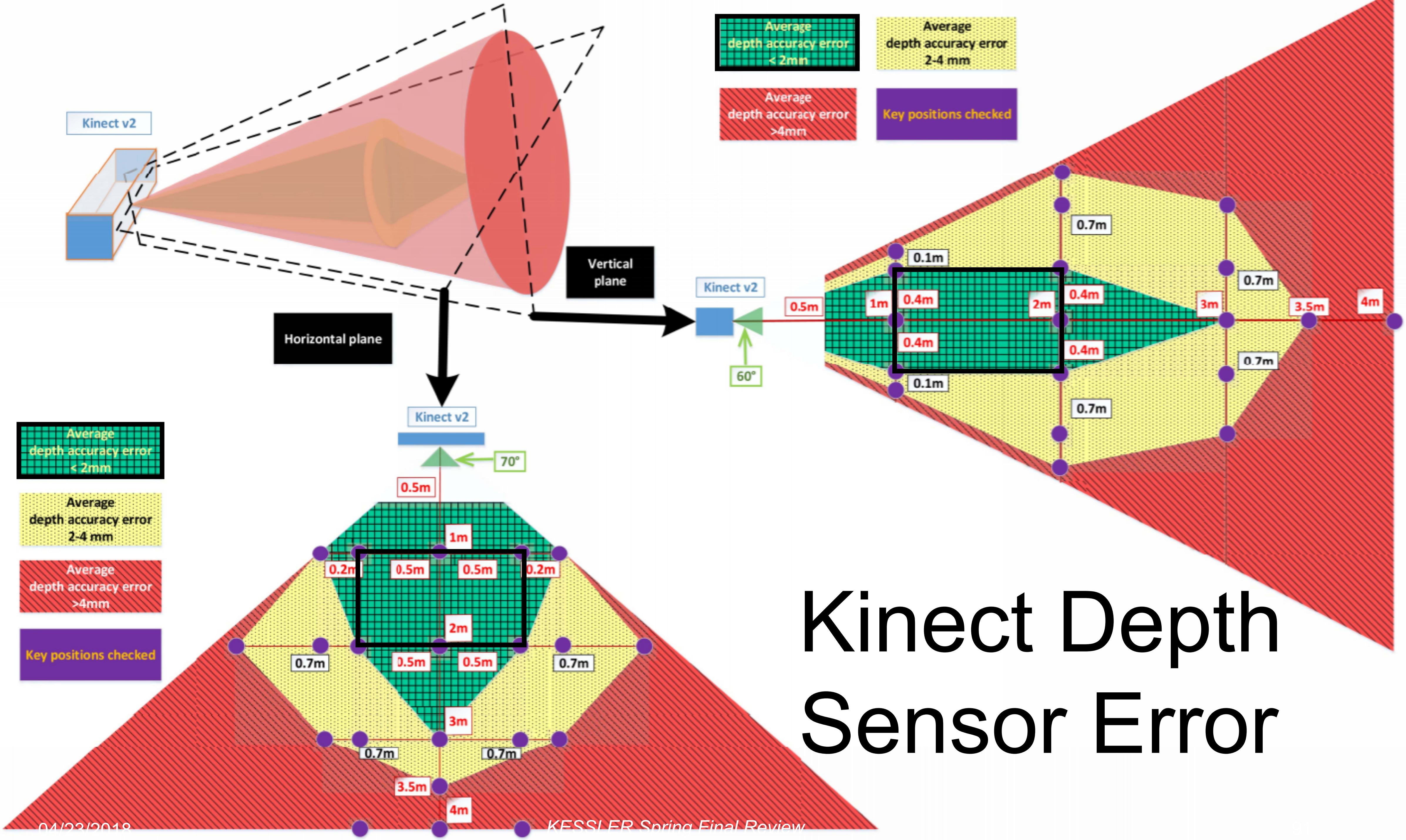
Design Requirements

REF ID	Description	Verification Method
D2.1	The end-effector position and orientation shall be determined in 3D space to within +/- 13mm and +/- 5 degrees.	Demonstration/Test
D2.2	The robotic arm path shall be constrained by the arm's joint limitations	Demonstration/Test

Design Requirements

REF ID	Description	Verification Method
D3.1	The robotic arm shall receive commands from the control system	Demonstration/Test
D3.2	Grappling features shall be representative of features on the Iridium Satellite form factor	Inspection Test
D3.3	Robotic arm shall execute path defined by control algorithm	Demonstration/Test
D3.4	End effector shall have a full deployable range of 9 inches.	Demonstration/Test
D3.5	The arm shall be capable of capturing feature at a finite displacement of 30inch arm radius, ± 180 degree roll, in x,y,z, and roll	Demonstration/Test

VP Backup



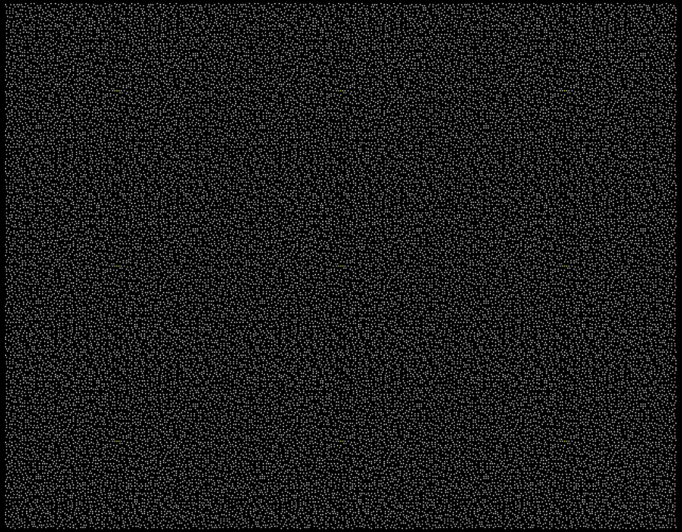
Kinect Depth Sensor Error

Camera Calibration

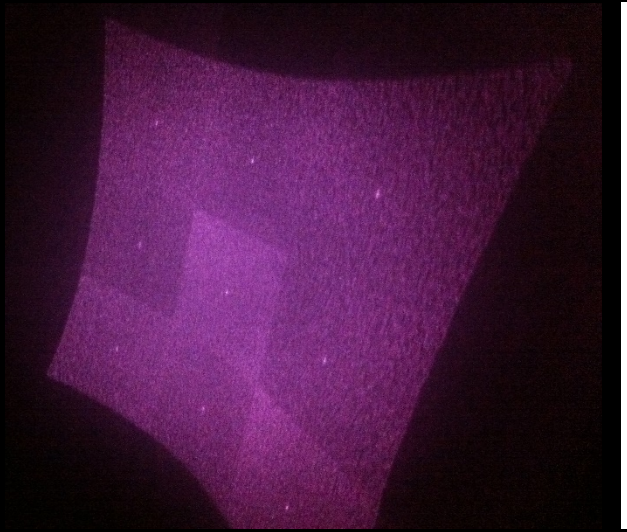
- Perform camera calibration on Kinect
    - Define possible pixel warping due to distance
- Take images of a checkerboard
- Determine differences between actual positions and measured positions
- Plot results to determine offset of Kinect

Fig #: Example of calibration testing setup

How the Kinect Works



https://azttm.wordpress.com/2011/04/03/kinect-pattern-uncovered/



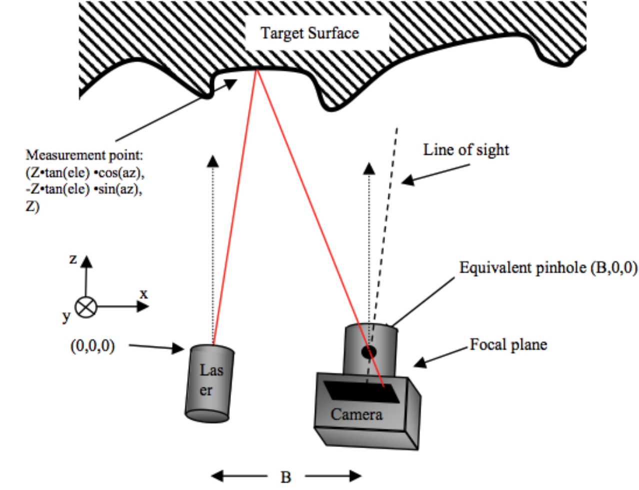


Figure 4 - Sketch of the non-idealized system

https://www.anandtech.com/show/4057/microsoft-kinect-the-anandtech-review/2

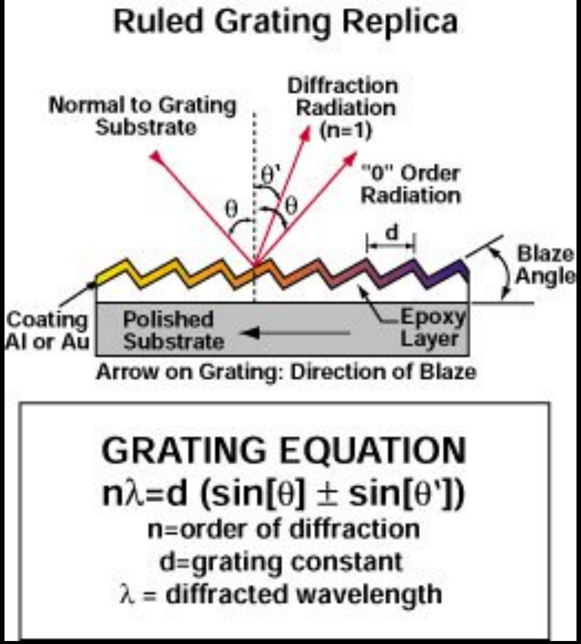
- Projected Structured Patterned Scene
- Distance between each dot is known
- Depth is determined from disparity
    - Offset of the Captured Pattern to the knows projected pattern
- Depth computations are performed on the Prime Sense’s PS1080 chip
- The actual pattern is distorted to a pin cushion shape and varies brightness.
- The pattern is composed of a 3×3 repetition of a 211 x 165 spot pattern, totaling to 633 x 495 spots, a number quite similar to VGA resolution.
- The pattern is additionally 180°-rotation invariant.
- Given a specific angle between emitter and sensor, depth can be recovered from simple triangulation. Expand this to a predictable structure, and the corresponding image shift directly relates to depth.

Capturing the IR Data Stream

- Kinect sensor returns *16 bits per* pixel infrared data with a resolution of *640 x 480* as an color image format, and it supports up to *30 FPS*.

Diffraction grating

- In optics, a diffraction grating is an optical component with a periodic structure that splits and diffracts light into several beams travelling in different directions. The directions of these beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as the dispersive element. The relationship between the grating spacing and the angles of the incident and diffracted beams of light is known as the grating equation.



https://abhijitjana.net/2013/01/11/get-the-ir-stream-and-control-the-ir-emitter-kinect-for-windows-sdk/

https://en.wikipedia.org/wiki/Diffraction_grating
https://www.edmundoptics.com/resources/faqs/optics/diffraction-gratings/what-is-the-grating-equation/

RA

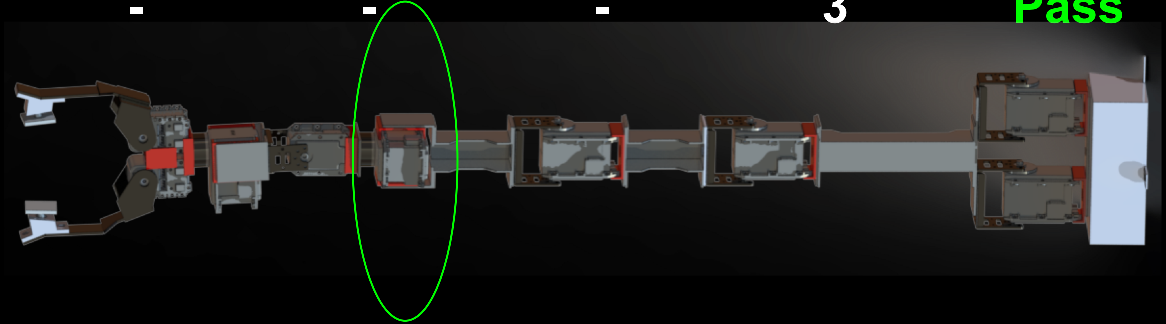
Actuator Dynamic Testing - Results

MX-64T Wrist (6)

Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
1,030	80	12.8	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass

MX-28T (7), H

Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
460	45	10.2	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass



Project Overview | Schedule | Software | **Hardware** | Integration | Budget

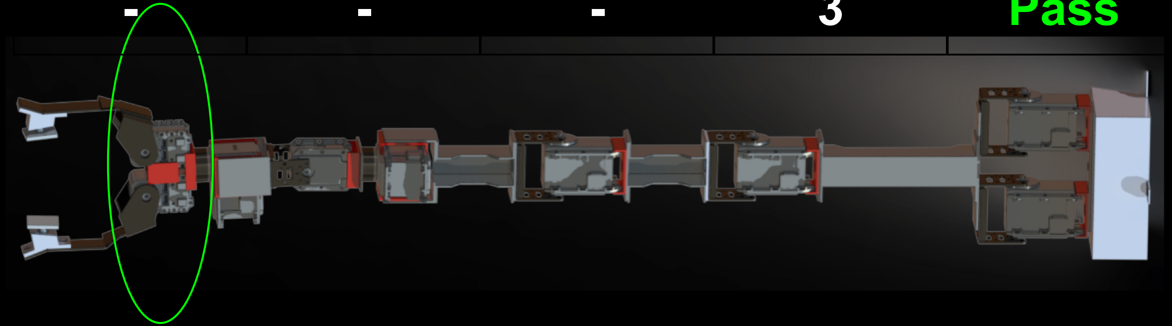
Actuator Dynamic Testing - Results

MX-28T Wrist (8), H (9,10), H

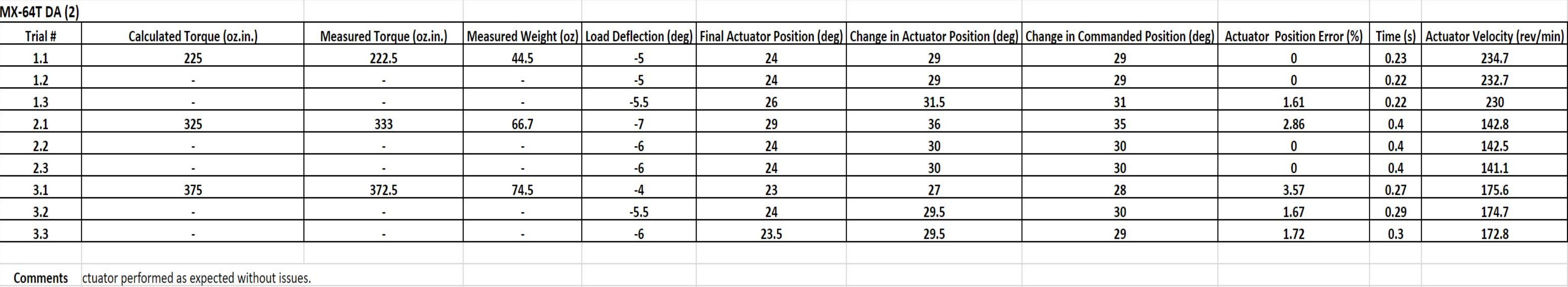
Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
460	20	25	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass

AX-12A

Stall Torque (oz.in)	Max Experienced Torque (oz.in)	Design FOS	Trial #	Pass/Fail
230	-	-	1	Pass
-	-	-	2	Pass
-	-	-	3	Pass

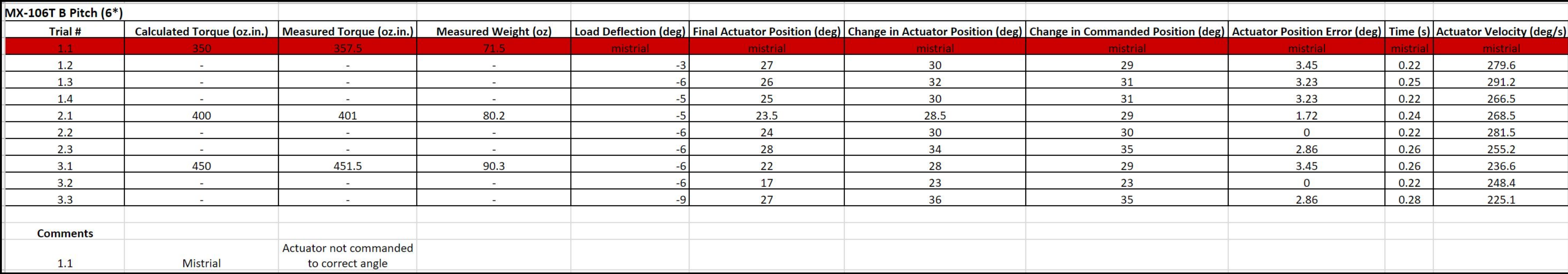


Actuator Preliminary Testing - Results



MX-64T DA (2)

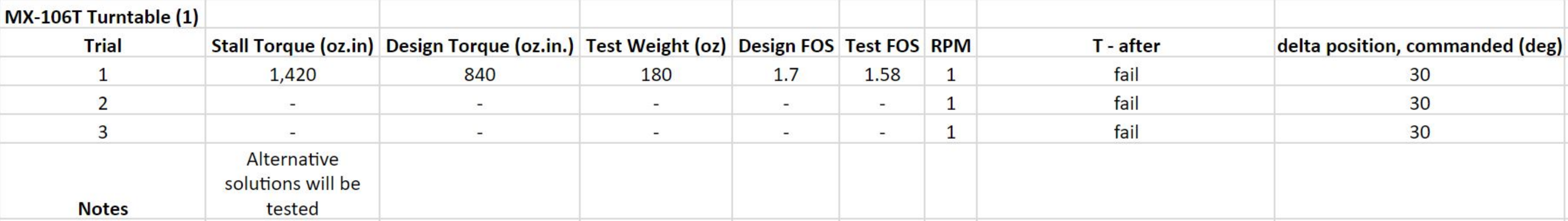
Trial #	Calculated Torque (oz.in.)	Measured Torque (oz.in.)	Measured Weight (oz)	Load Deflection (deg)	Final Actuator Position (deg)	Change in Actuator Position (deg)	Change in Commanded Position (deg)	Actuator Position Error (%)	Time (s)	Actuator Velocity (rev/min)
1.1	225	222.5	44.5	-5	24	29	29	0	0.23	234.7
1.2	-	-	-	-5	24	29	29	0	0.22	232.7
1.3	-	-	-	-5.5	26	31.5	31	1.61	0.22	230
2.1	325	333	66.7	-7	29	36	35	2.86	0.4	142.8
2.2	-	-	-	-6	24	30	30	0	0.4	142.5
2.3	-	-	-	-6	24	30	30	0	0.4	141.1
3.1	375	372.5	74.5	-4	23	27	28	3.57	0.27	175.6
3.2	-	-	-	-5.5	24	29.5	30	1.67	0.29	174.7
3.3	-	-	-	-6	23.5	29.5	29	1.72	0.3	172.8
Comments	ctuator performed as expected without issues.									



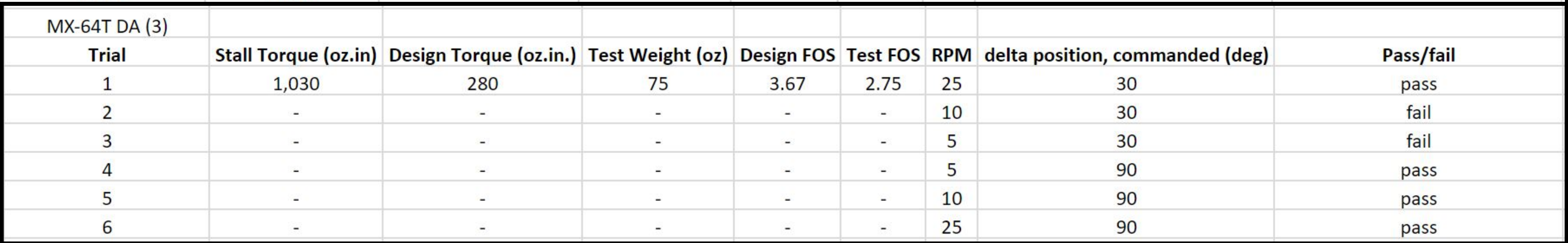
MX-106T B Pitch (6*)

Trial #	Calculated Torque (oz.in.)	Measured Torque (oz.in.)	Measured Weight (oz)	Load Deflection (deg)	Final Actuator Position (deg)	Change in Actuator Position (deg)	Change in Commanded Position (deg)	Actuator Position Error (deg)	Time (s)	Actuator Velocity (deg/s)
1.1	350	357.5	71.5	mistrial	mistrial	mistrial	mistrial	mistrial	mistrial	mistrial
1.2	-	-	-	-3	27	30	29	3.45	0.22	279.6
1.3	-	-	-	-6	26	32	31	3.23	0.25	291.2
1.4	-	-	-	-5	25	30	31	3.23	0.22	266.5
2.1	400	401	80.2	-5	23.5	28.5	29	1.72	0.24	268.5
2.2	-	-	-	-6	24	30	30	0	0.22	281.5
2.3	-	-	-	-6	28	34	35	2.86	0.26	255.2
3.1	450	451.5	90.3	-6	22	28	29	3.45	0.26	236.6
3.2	-	-	-	-6	17	23	23	0	0.22	248.4
3.3	-	-	-	-9	27	36	35	2.86	0.28	225.1
Comments										
1.1	Mistrial	Actuator not commanded to correct angle								

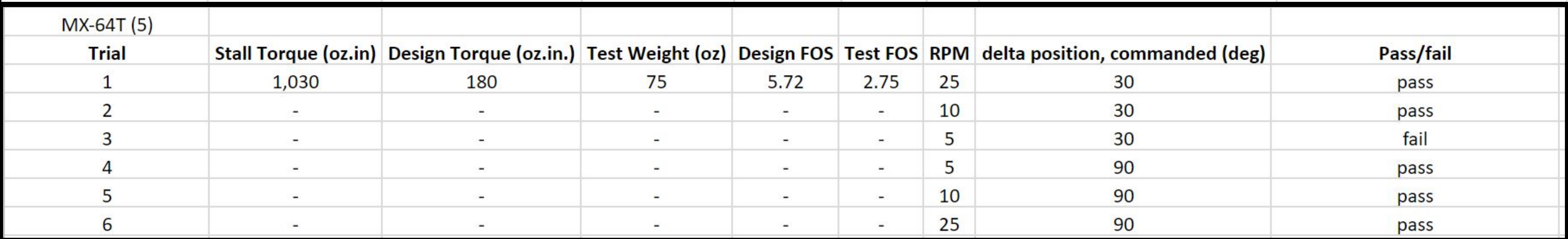
Actuator Testing - Results



MX-106T Turntable (1)								
Trial	**Stall Torque (oz.in)**	**Design Torque (oz.in.)**	**Test Weight (oz)**	**Design FOS**	**Test FOS**	**RPM**	**T - after**	**delta position, commanded (deg)**
1	1,420	840	180	1.7	1.58	1	fail	30
2	-	-	-	-	-	1	fail	30
3	-	-	-	-	-	1	fail	30
Notes	Alternative solutions will be tested							

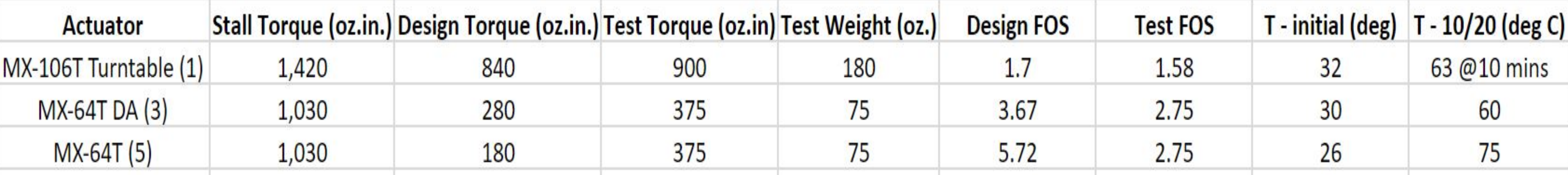


MX-64T DA (3)								
Trial	**Stall Torque (oz.in)**	**Design Torque (oz.in.)**	**Test Weight (oz)**	**Design FOS**	**Test FOS**	**RPM**	**delta position, commanded (deg)**	**Pass/fail**
1	1,030	280	75	3.67	2.75	25	30	pass
2	-	-	-	-	-	10	30	fail
3	-	-	-	-	-	5	30	fail
4	-	-	-	-	-	5	90	pass
5	-	-	-	-	-	10	90	pass
6	-	-	-	-	-	25	90	pass



MX-64T (5)								
Trial	**Stall Torque (oz.in)**	**Design Torque (oz.in.)**	**Test Weight (oz)**	**Design FOS**	**Test FOS**	**RPM**	**delta position, commanded (deg)**	**Pass/fail**
1	1,030	180	75	5.72	2.75	25	30	pass
2	-	-	-	-	-	10	30	pass
3	-	-	-	-	-	5	30	fail
4	-	-	-	-	-	5	90	pass
5	-	-	-	-	-	10	90	pass
6	-	-	-	-	-	25	90	pass

Actuator Testing - Results



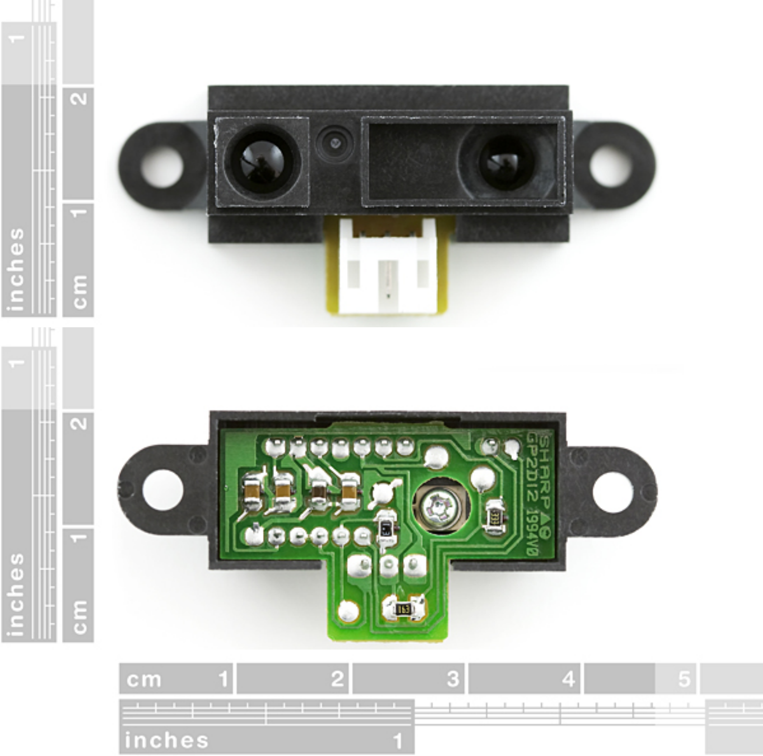
Actuator	Stall Torque (oz.in.)	Design Torque (oz.in.)	Test Torque (oz.in)	Test Weight (oz.)	Design FOS	Test FOS	T - initial (deg)	T - 10/20 (deg C)
MX-106T Turntable (1)	1,420	840	900	180	1.7	1.58	32	63 @10 mins
MX-64T DA (3)	1,030	280	375	75	3.67	2.75	30	60
MX-64T (5)	1,030	180	375	75	5.72	2.75	26	75

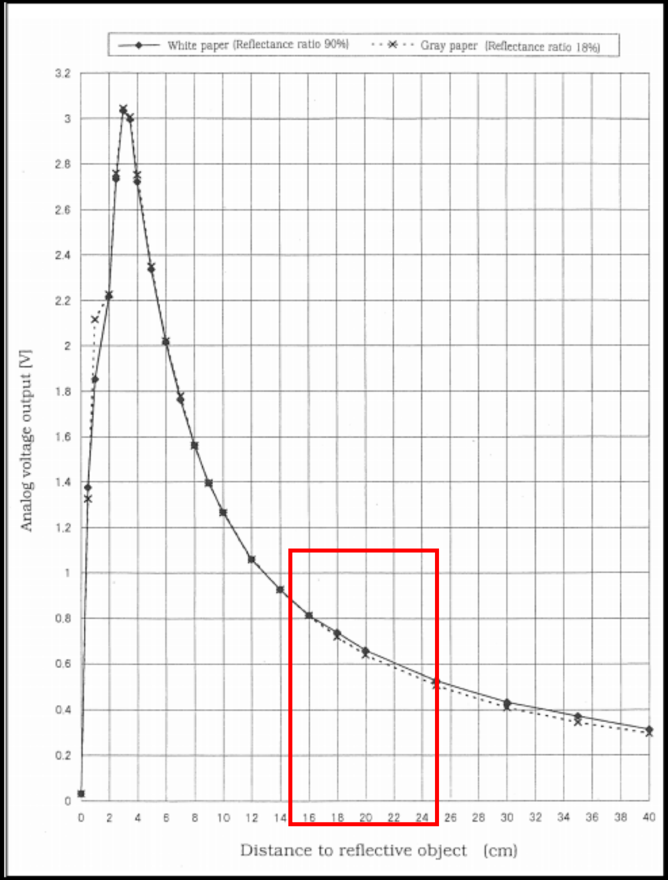
ELEC

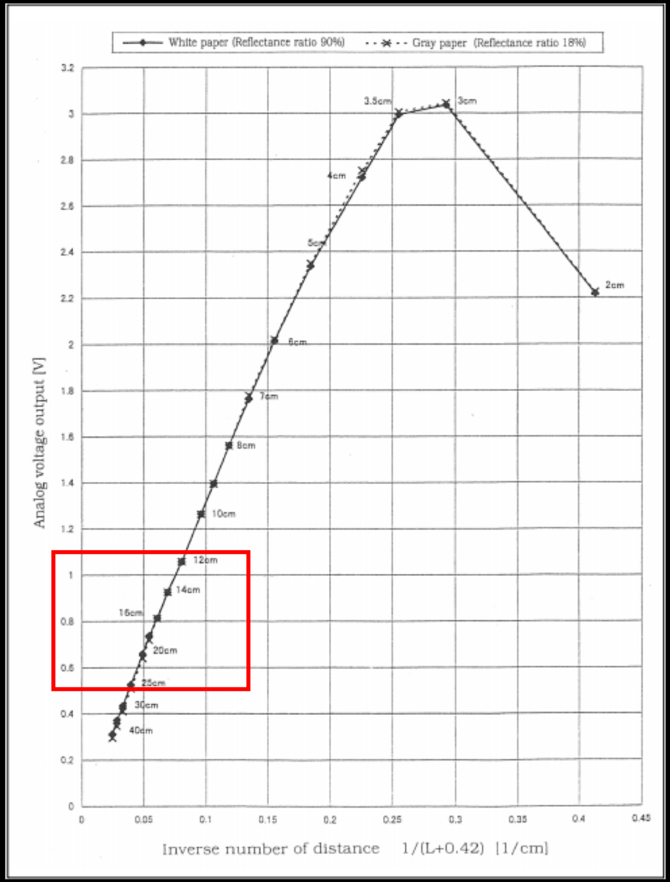
Hardware Update: Proximity Sensor

Sharp Infrared Proximity Short Range Sensor

- 16.5 ms ± 3.7 ms data acquisition rate







Electrical Hardware Block Diagram

Short Range Camera (src) and Proximity Sensor: Harnessing for communication and integration with microcontroller.

Microcontroller: USB to MicroUSB, expected location central to PC.

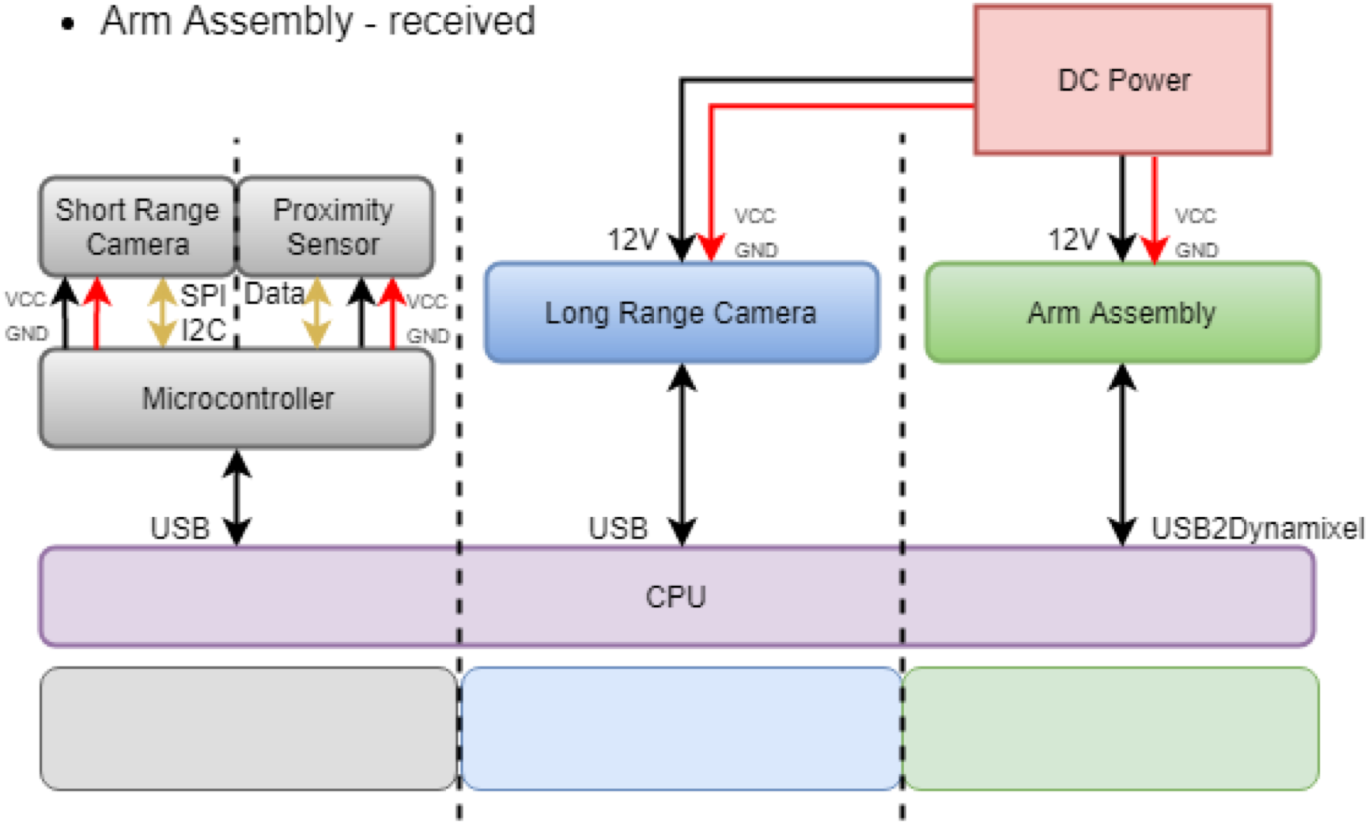
Long Range Camera: External DC Power Supply and USB cord management

Arm Assembly: Anchors for SRC harnessing, removal of heritage force cells, re-harnessing of heritage actuator 3-pin connectors.

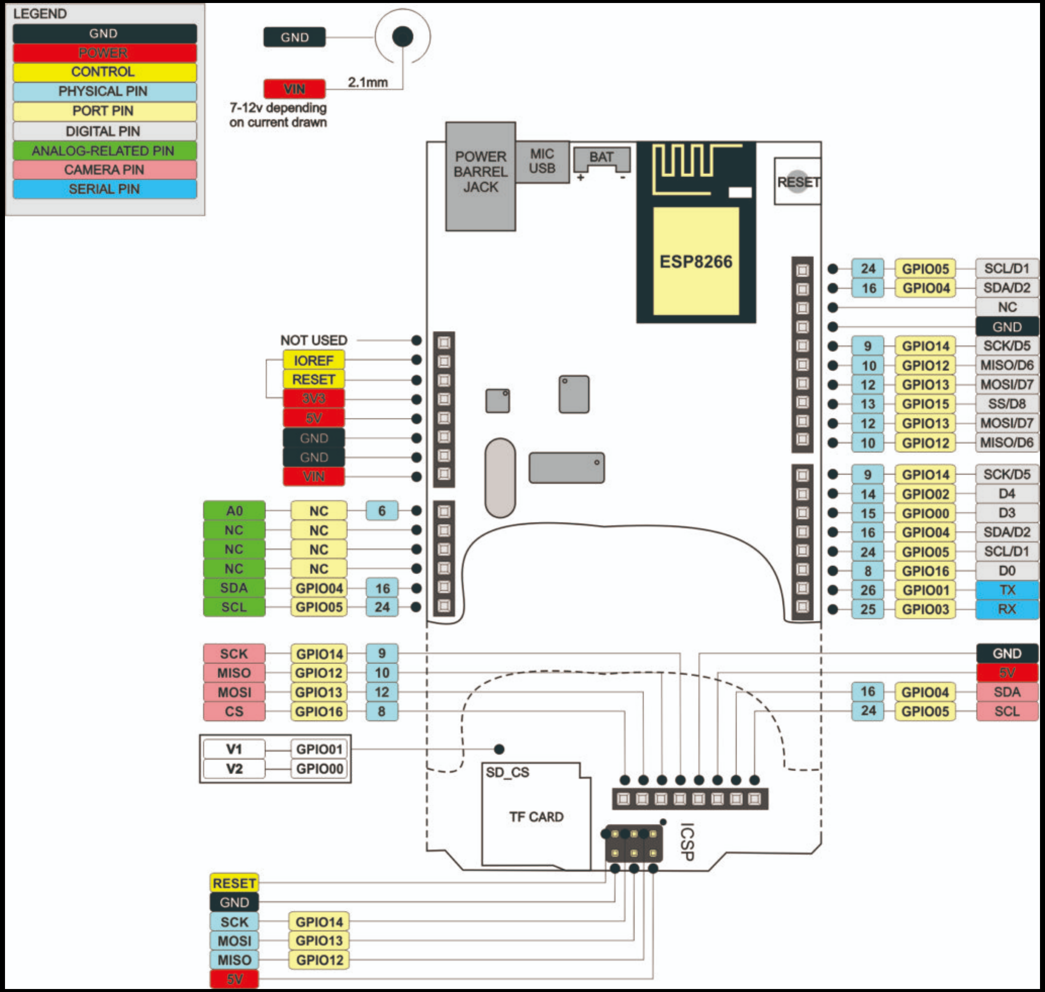
<u>**Expected Challenge**</u>:
Verifying SRC harnessing provides reliable connectivity and does not impede arm execution.

Electronics Hardware Housing and Integration

- Short Range Camera, Microcontroller - received
- Proximity Sensor - received
- Long Range Camera - heritage
- Arm Assembly - received



ArduCam Uno

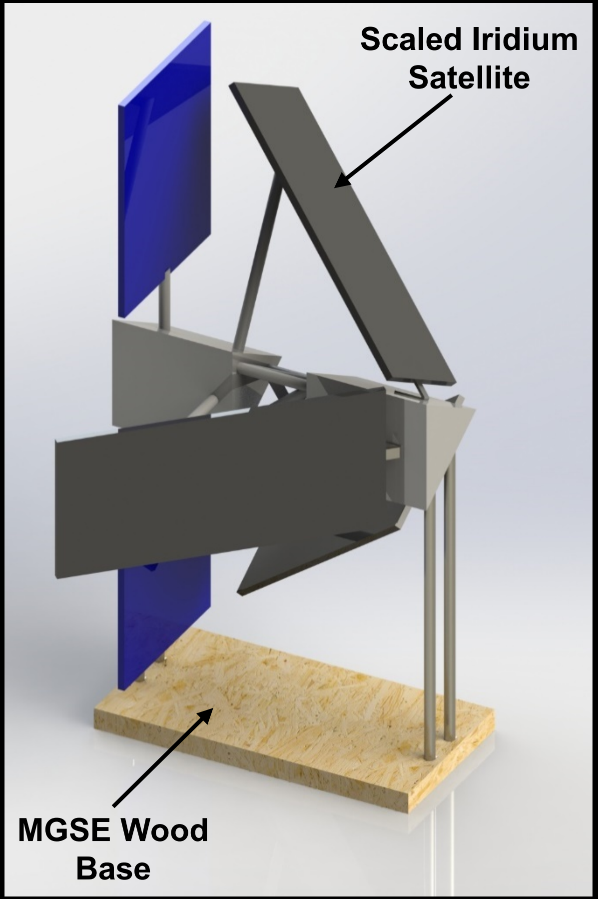


- Power
  - 3.3 to 5 VCC and GND
- SPI
  - Issues capture command; ArduCam waits for new frame and buffers the entire image data to the frame buffer, sets completion flag bit
- I2C
  - Interacts directly with the OV2640 image sensor

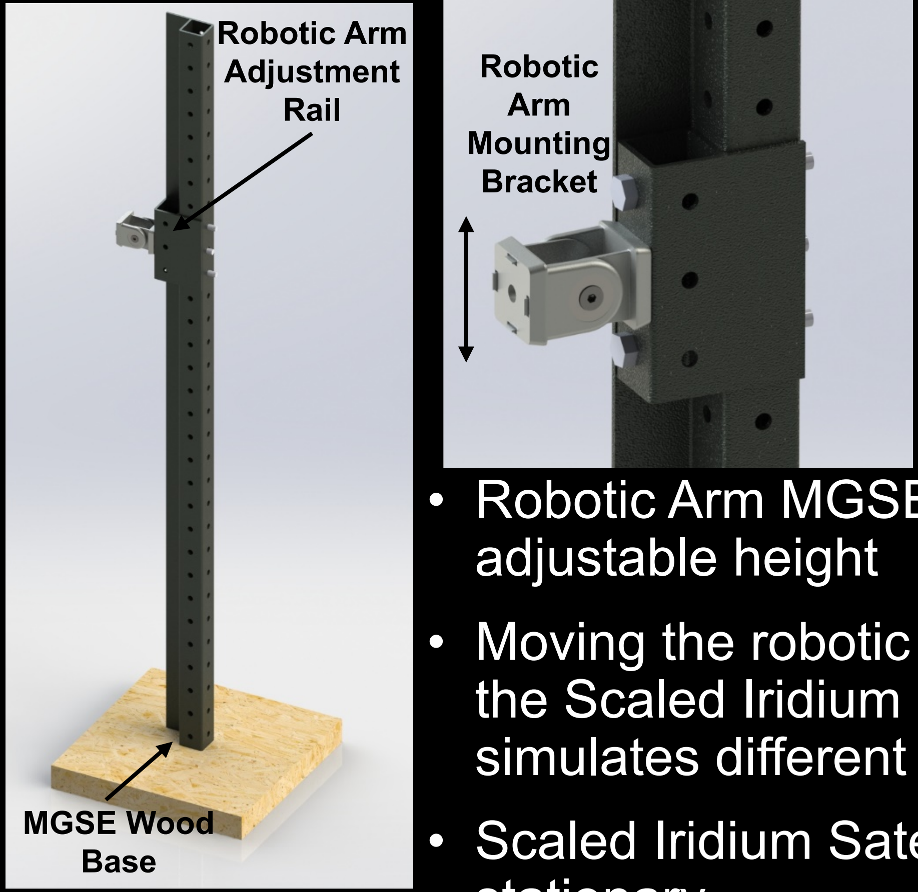
INTEG

System Ground Support Equipment

Scaled Iridium Satellite MGSE



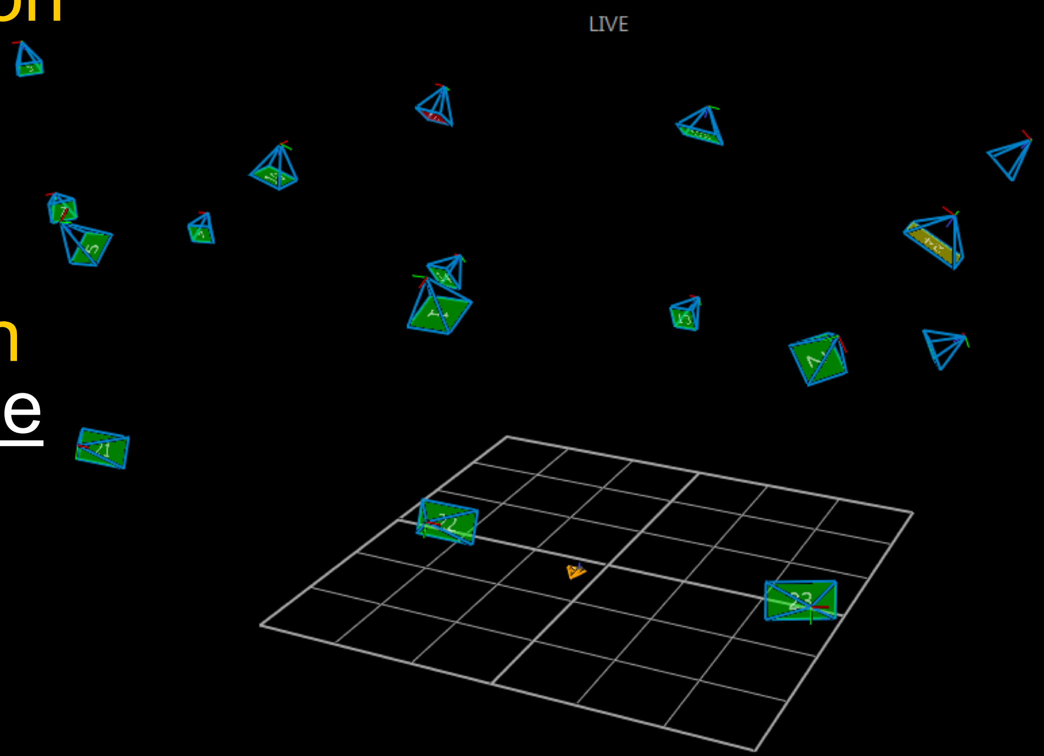
Robotic Arm MGSE



- Robotic Arm MGSE is movable and has adjustable height
- Moving the robotic arm MGSE around the Scaled Iridium Satellite MGSE simulates different approaches
- Scaled Iridium Satellite will be kept stationary

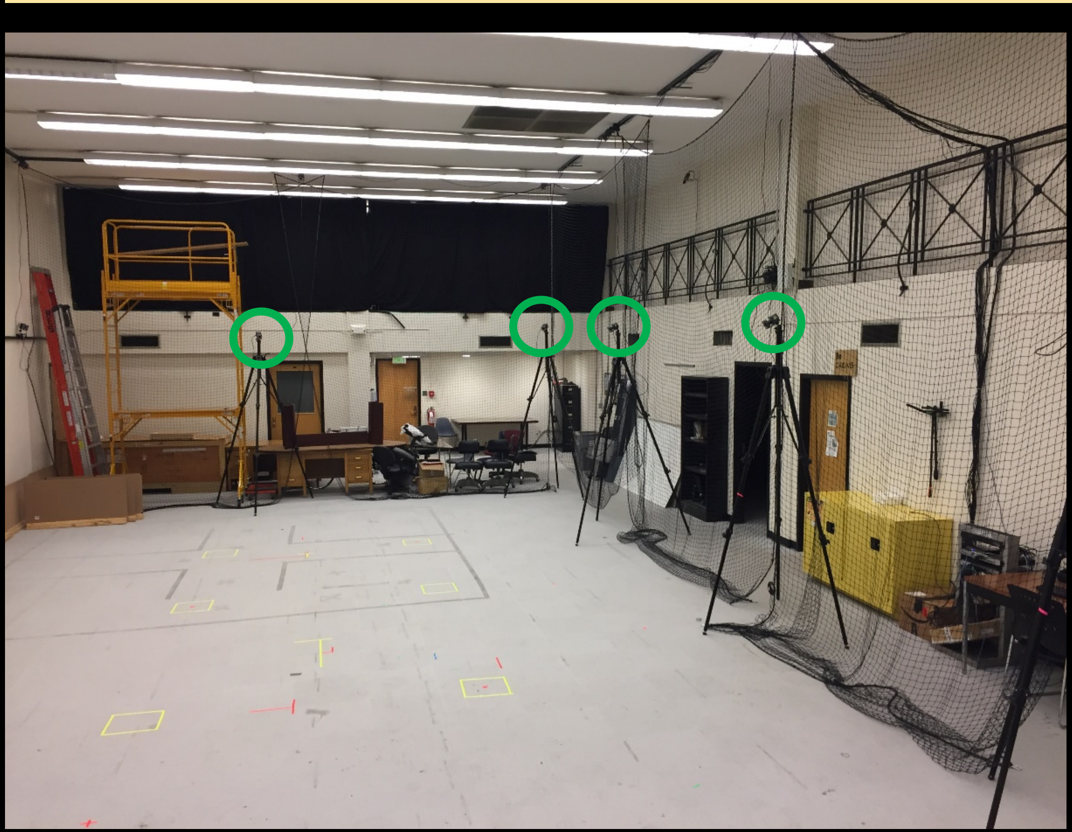
VICON

- VICON is a system of cameras that measures the position and orientation of an object marked with markers
- Has an accuracy of 1mm when measuring stationary objects
- VICON is able to measure objects in motion at 120 fps, but we will not use this functionality
- VICON data is only truth data. KESSLER will not use VICON for operation, only for conformation



Visualization of VICON cameras around an object

RIFLE lab



Picture of the RECUV Indoor FLight Environment (RIFLE)

A single VICON Camera

- RIFLE has 18 VICON cameras
- Positions of the cameras are adjustable to maximize visibility to the measured object

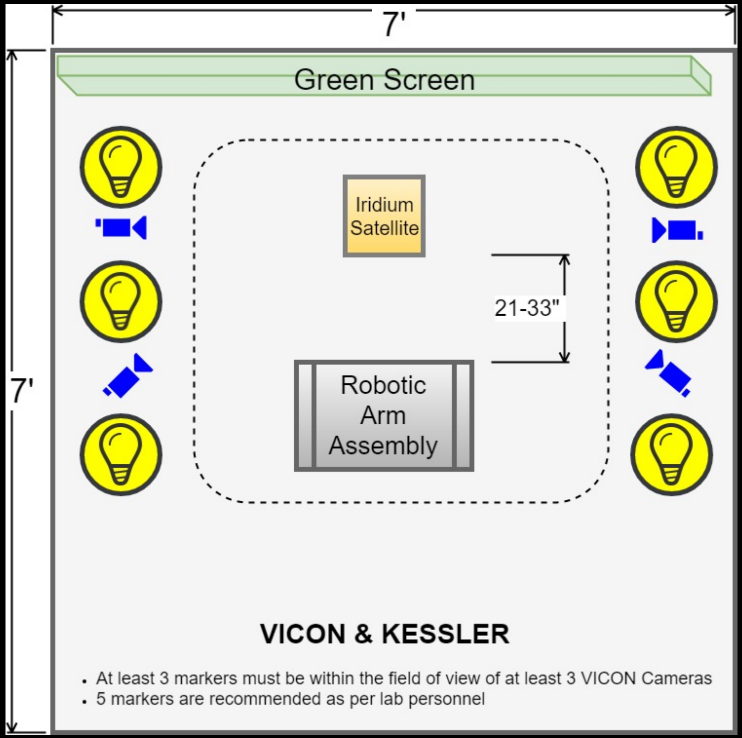
Final Integration Test Procedure

1. Green Screen, Lighting System and VICON will be set up. VICON will be calibrated.
2. Iridium satellite and Robotic Arm MGSE's will be set up. The approach of the arm will be varied by changing the position of the Robotic Arm MGSE.
3. KESSLER will begin operation:
    - Visual Processing Algorithm will find closest point of Satellite (Level 1) or closest plane (Level 2 and 3). Then it will pass position (Level 1), orientation (if Level 2), and avoidance point cloud (if Level 3)
    - Controls Algorithm will generate a path to the point given to it by Visual Processing, while avoiding collision (if Level 3).
    - Controls Algorithm will output commands to arm, and arm shall execute path made by controls. End Effector will end up at a point (and orientation if Level 2) initially output by the Visual System.
    - **Position of end effector will now be measured with VICON**
    - Claw will actuate and grip target (if Level 2 and 3). System will be inspected to ensure that claw has gripped the target, and torque of claw will be measured
4. KESSLER will finish operation. Time of Operation is recorded.

Level 1
Level 2
Level 3

Project Overview → **Schedule** → **Software** → **Hardware** → **Integration** → **Budget**

Final Integration Test Objectives



- At least 3 markers must be within the field of view of at least 3 VICON Cameras
- 5 markers are recommended as per lab personnel

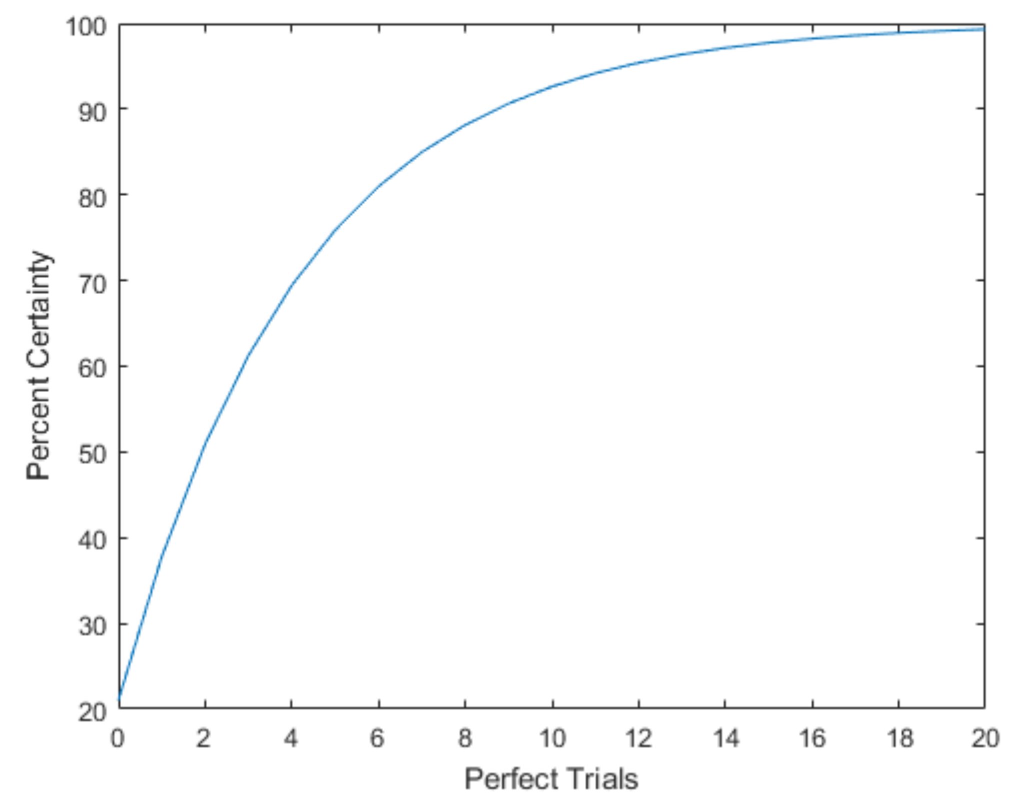
Verify Functional Requirements:

1. The visual processing algorithm shall identify the position and orientation of a satellite.
2. Control algorithm shall define a path from the initial to final end-effector position and orientation.
3. Robotic arm shall autonomously navigate to at least one preselected grappling feature on the satellite.
4. KESSLER shall have a total mission time no greater than 53 minutes, based off the average LEO orbital period.
5. KESSLER shall execute a total 3 end to end process operations and succeed at least twice within the total mission time.

System Reliability

D5.0: KESSLER shall execute a total 3 end to end process operations and succeed at least twice within the total mission time.

- To execute this requirement reliably (>90% success), KESSLER as a system must have a success rate in individual tests (R) of 79%. Found with $R^3 + 3(1-R)R^2 = 0.9$
- Bimodal Distribution, $P(X = x) = (nCs)R^s(1-R)^{n-s}$, can be used to quantify success rate.
- Using this approach can cut down on number of tests required to be confident in results.



How certain we can be that KESSLER has over 79% reliability based on consecutive successful trials

Section 6 Backup

Project Management Approach

- Initial Approach (prior to project selection)
  - Contacted peers from previous lab work that worked well together
  - Valued "Team Dynamic and Skill Versatility over Project Topic"
  - Voted on highest technical interests for Project Bazaar
- Post Project Selection
  - **Milestone driven** – Course milestones provided strong infrastructure
  - Defined sub-milestones as a team to ensure we had team buy-in for all majors tasks
  - Conducted weekly meetings with Project Customer and Project Advisor every Thursday
    - Held presentation 'design reviews' leading into course milestones

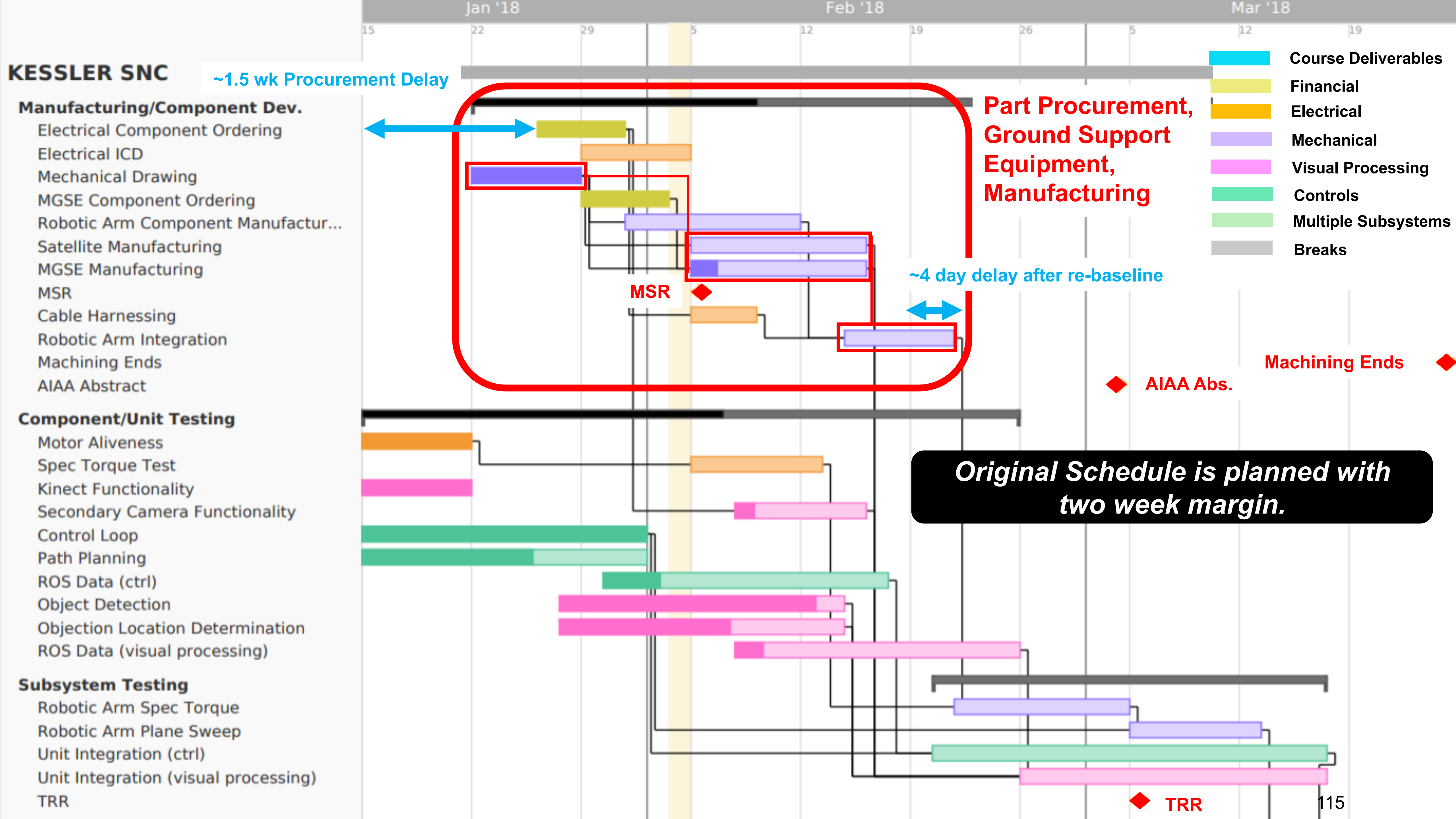
Project Overview | Design Description | Test Overview | Test Results | Systems Engineering | Project Management

Project Management Approach

- Fall 2017 – Subsystem Autonomy
  - Subsystems delivered required data for milestones
    - PM & SE helped to define sub-milestones (with input from team)
    - Sub-milestones reviewed by team (customer & advisor too) during Thursday meetings
    - Templates were provided for higher efficiency to reuse work for course deliverables
  - All subsystems were required to meet at least once a week outside of lab hours
- Spring 2018 – Inter-Subsystem Development
  - Majority of working hours involved at least 7/11 team members
  - Working hours lasted between 4-8 hours depending on project phase
    - Deliverable development vs. integration testing

Presentation 'content reviews' held Thursdays prior to Monday submissions. Upon feedback received we met with PAB to help rectify / clarify any issues.

Project Overview
Design Description
Test Overview
Test Results
Systems Engineering
Project Management

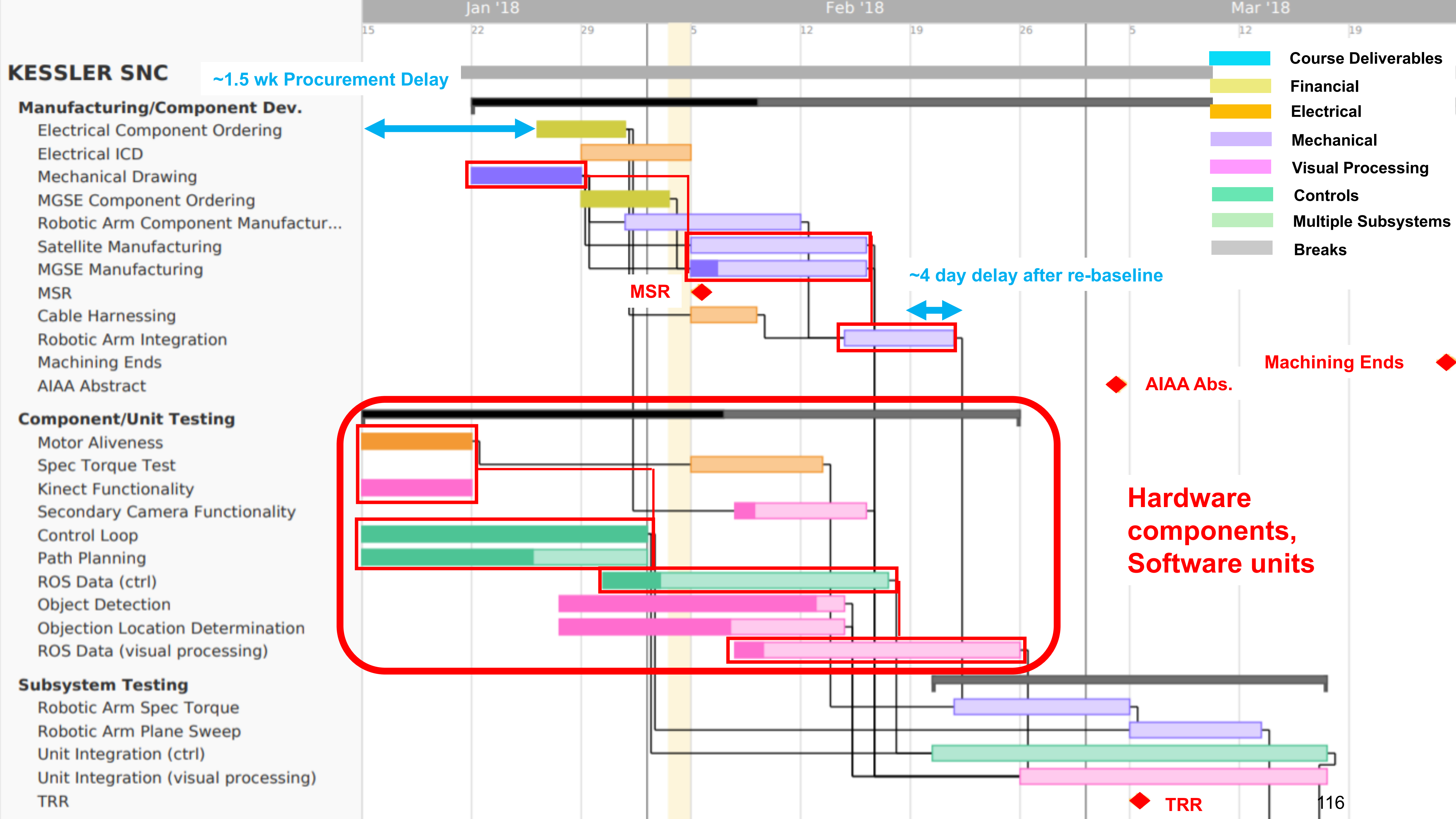


~1.5 wk Procurement Delay

Part Procurement, Ground Support Equipment, Manufacturing

~4 day delay after re-baseline

Original Schedule is planned with two week margin.



KESSLER SNC

Manufacturing/Component Dev.
- Electrical Component Ordering
- Electrical ICD
- Mechanical Drawing
- MGSE Component Ordering
- Robotic Arm Component Manufactur...
- Satellite Manufacturing
- MGSE Manufacturing
- MSR
- Cable Harnessing
- Robotic Arm Integration
- Machining Ends
- AIAA Abstract

Component/Unit Testing
- Motor Aliveness
- Spec Torque Test
- Kinect Functionality
- Secondary Camera Functionality
- Control Loop
- Path Planning
- ROS Data (ctrl)
- Object Detection
- Objection Location Determination
- ROS Data (visual processing)

Subsystem Testing
- Robotic Arm Spec Torque
- Robotic Arm Plane Sweep
- Unit Integration (ctrl)
- Unit Integration (visual processing)
- TRR

~1.5 wk Procurement Delay

~4 day delay after re-baseline

MSR

Machining Ends

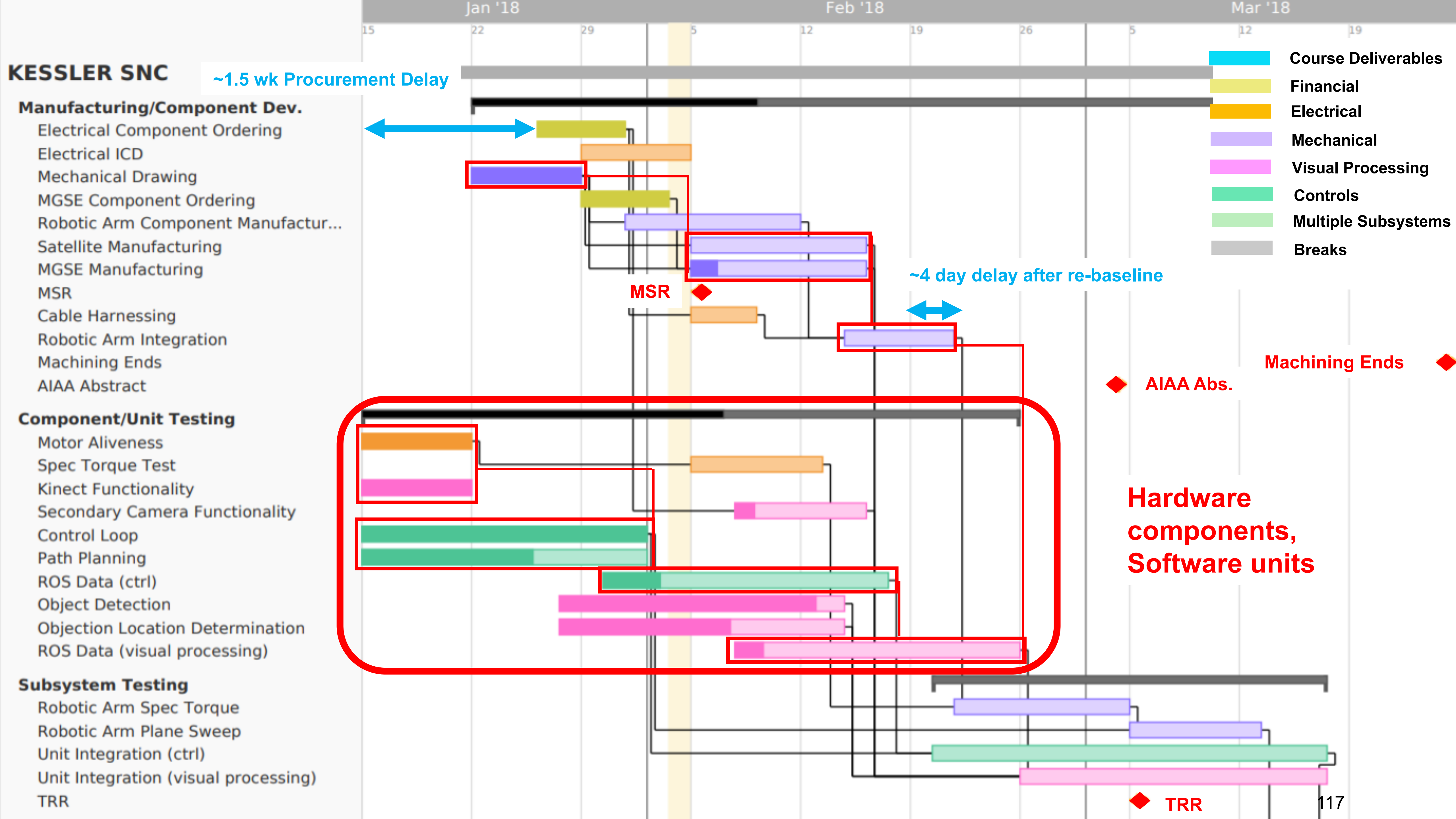
AIAA Abs.

TRR

Hardware components, Software units

- 🟦 Course Deliverables
- 🟨 Financial
- 🟧 Electrical
- 🟪 Mechanical
- 🟪 Visual Processing
- 🟩 Controls
- 🟩 Multiple Subsystems
- ⬜ Breaks

KESSLER SNC



Manufacturing/Component Dev.
- Electrical Component Ordering
- Electrical ICD
- Mechanical Drawing
- MGSE Component Ordering
- Robotic Arm Component Manufactur...
- Satellite Manufacturing
- MGSE Manufacturing
- MSR
- Cable Harnessing
- Robotic Arm Integration
- Machining Ends
- AIAA Abstract

Component/Unit Testing
- Motor Aliveness
- Spec Torque Test
- Kinect Functionality
- Secondary Camera Functionality
- Control Loop
- Path Planning
- ROS Data (ctrl)
- Object Detection
- Objection Location Determination
- ROS Data (visual processing)

Subsystem Testing
- Robotic Arm Spec Torque
- Robotic Arm Plane Sweep
- Unit Integration (ctrl)
- Unit Integration (visual processing)
- TRR

Course Deliverables
Financial
Electrical
Mechanical
Visual Processing
Controls
Multiple Subsystems
Breaks

~1.5 wk Procurement Delay

~4 day delay after re-baseline

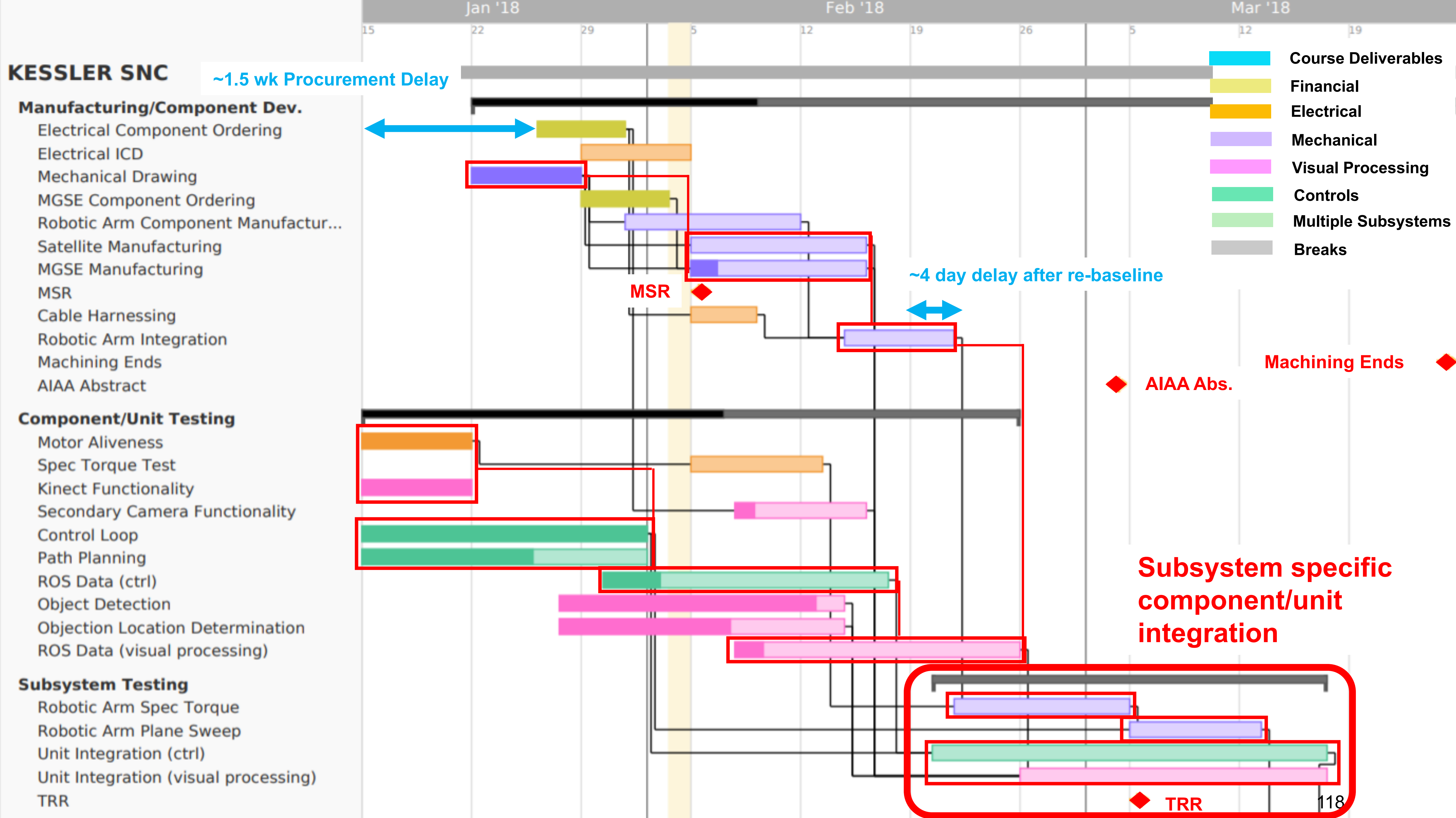
MSR

AIAA Abs.

Machining Ends

TRR

Hardware components, Software units



KESSLER SNC

~1.5 wk Procurement Delay

Manufacturing/Component Dev.
- Electrical Component Ordering
- Electrical ICD
- Mechanical Drawing
- MGSE Component Ordering
- Robotic Arm Component Manufactur...
- Satellite Manufacturing
- MGSE Manufacturing
- MSR
- Cable Harnessing
- Robotic Arm Integration
- Machining Ends
- AIAA Abstract

Component/Unit Testing
- Motor Aliveness
- Spec Torque Test
- Kinect Functionality
- Secondary Camera Functionality
- Control Loop
- Path Planning
- ROS Data (ctrl)
- Object Detection
- Objection Location Determination
- ROS Data (visual processing)

Subsystem Testing
- Robotic Arm Spec Torque
- Robotic Arm Plane Sweep
- Unit Integration (ctrl)
- Unit Integration (visual processing)
- TRR

MSR

~4 day delay after re-baseline

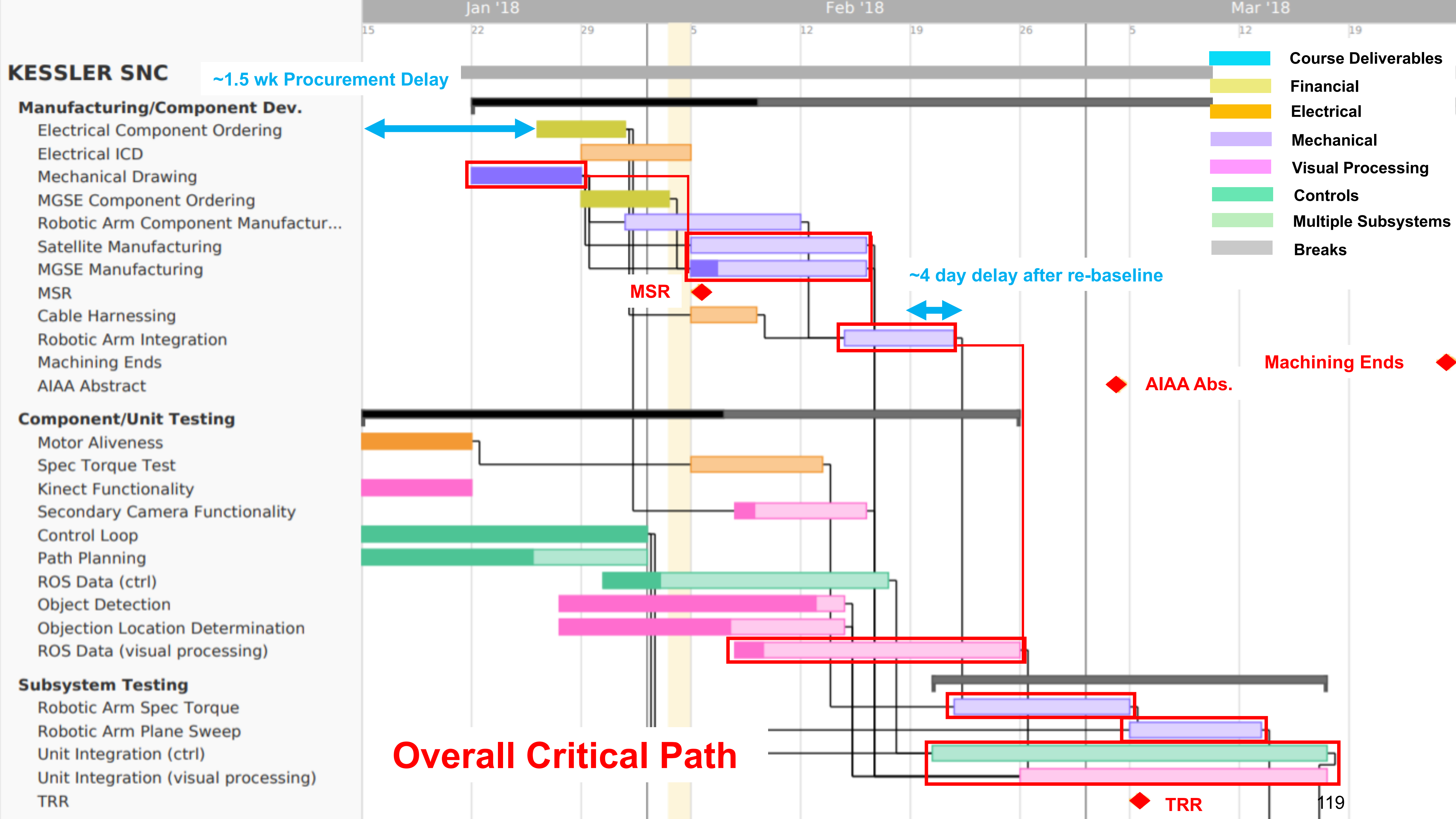
Machining Ends

AIAA Abs.

Subsystem specific component/unit integration

TRR

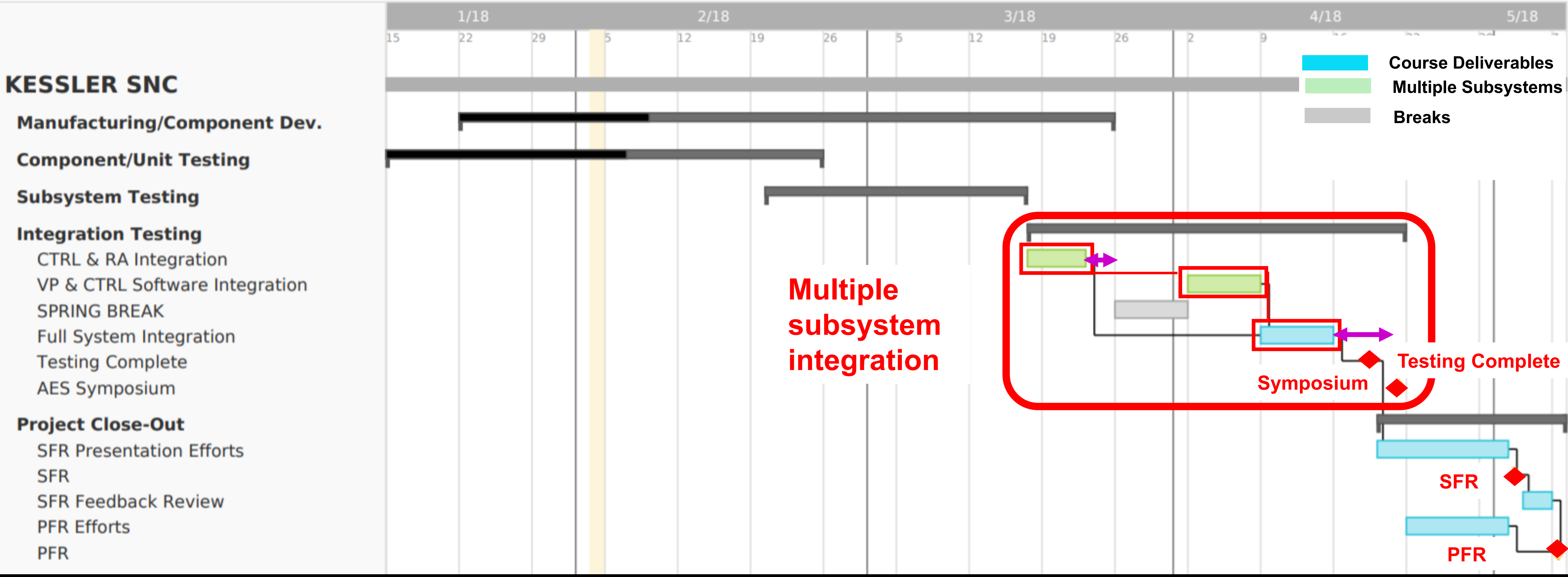
- Course Deliverables
- Financial
- Electrical
- Mechanical
- Visual Processing
- Controls
- Multiple Subsystems
- Breaks



~1.5 wk Procurement Delay

~4 day delay after re-baseline

Overall Critical Path



- 1 week net margin
- 0.5 week conservative scheduling for integration
- Spring Break not counted but usable time (extra week)

Current Schedule is planned with 1.5 week margin.

Budget

Subsystem	Cost	Items
Visual Processing	$296.24	ArduCam, Arduino, Lighting, Green Screen, Spray paint, power strips
Mechanical	$3,357.97	CrustCrawler parts (girders, fasteners, **replacement servos**)
Software Control	$0.00	N/A
Ground & Test Support	$826.03	Acrylic, fasteners, paint, plywood
Electrical	$236.56	Power, connectors, sensors, sleeving
Misc.	$77.98	Printing, etc.
Total Cost	$4,794.78	
Remaining	$205.22	

Updated 4/19/2018

Visual Processing

Item (Name)	Price (per unit, without tax)	Quantity	Item Total
ArduCAM Mini	$25.99	1	$25.99
Arduino Zero	$39.00	1	$39.00
Lighting	$48.22	2	$96.44
		0	$0.00
Green screen	$26.99	1	$26.99
Green screen stand	$32.50	1	$32.50
Gold spray paint	$6.76	1	$6.76
Silver spray paint	$6.76	1	$6.76
Black spray paint	$5.76	1	$5.76
White spray paint	$3.28	2	$6.56
Extra lightbulbs	$34.90	1	$34.90
Power strips	$10.89	1	$10.89

Visual Processing	$296.24
Total	$4,794.78

Updated 4/19/2018

Mechanical

Item (Name)	Price (per unit, without tax)	Quantity	Item Total
MX-106T	$552.00	1	$552.00
MX-64T Wrist	$364.00	1	$364.00
2.5" Girder	$23.00	2	$46.00
MX-64/106 To MX-28 Adapter	$11.99	2	$23.98
Singleaxismount	$15.00	3	$45.00
12in. (30.48cm) 3-pin wire extension	$9.49	3	$28.47
5" Girder	$29.00	1	$29.00
Fasteners (various)	$64.31	1	$64.31
AX Dual Gripper kit (no servo)	$69.00	1	$69.00
FR08-H101	$29.90	1	$29.90
FR05-H101K	$29.90	1	$29.90
FR07-H101	$27.90	1	$27.90
MX-28T (servo only)	$219.90	1	$219.90
Stanley Organizer	$14.40	2	$28.80
Various Hardware	$335.61	1	$335.61
MX-106T DA	$1,166.00	1	$1,166.00
Fiero	$45.68	1	$45.68

Mechanical	$3,357.97
Total	$4,794.78

Updated 4/19/2018